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Scotopic Sensitivity Syndrome in a Single Individual (A Case Study)

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FOREWORD

This endeavor was initiated by the Naval Air Warfare Center's Fleet Training Support Office as part of an Independent Research Bid and Proposal effort. The study was originally conceived as a small preliminary look at feasibility: to be used as back up for its research proposal. However as the study unfolded and produced significant new scientific findings, it was decided that the nature of the findings were such, as to require publication of the findings in report form. The subject report should be viewed as a compilation of research notes, methodical studies, working study papers, and basic findings rather than a finished overview of the subject area.

The work described in this report was performed at the Naval Air Warfare Center Weapons Division, China Lake, Calif., from July 1992 to January 1997 and funded as independent research by the System Management Office, Planning and Management Department, China Lake. The report was prepared for timely presentation and is released at the working level.

R. M. DECKER, Head
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14. ABSTRACT

(U) In 1983, Helen Irlen discovered that some dyslexic individuals could be helped by manipulating the optical frequency spectrum presented to their eyes (the Irlen Phenomenon). Although it is accepted in several countries, this technique was considered somewhat controversial. The current study investigates this form of visual dyslexia to determine its legitimacy and the possibility of developing an experimental methodology to quantify and study the phenomenon in Fleet personnel, with the ultimate goal of improving Fleet training.

(U) This case study substantiates the existence of the Irlen phenomenon through experimental research with a test subject (utilizing the "lay on" filtering technique developed by Irlen in 1983) and application of the modern Receptor Field Theory of Human Vision. Study findings indicate that the energy spectrum presented to the eye of a dyslexic is capable of altering visual and cognitive performance to a significant extent for both better and worse. The experimental methods developed by this study can be used to quantify the performance of Irlen-type dyslexics and to study the impact of visual spectral energy on their vision system.

(U) Based on these findings, potentially 10 to 20% of Naval personnel could experience improvement in performance and efficiency through a simple modification of the work environment lighting system.

15. SUBJECT TERMS
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EXECUTIVE SUMMARY

BACKGROUND

Dyslexia is a condition known to affect 10% to 15% of the human race. In 1983 Helen Irlen of the University of California, Long Beach, discovered that some individuals with dyslexia could be helped by manipulating the optical frequency spectrum presented to their eyes. This has been a somewhat controversial treatment for several years, partly because no theoretical basis exists for it to work in visual physiology, even though the treatment is now accepted in several countries.

Based on interest expressed by the Naval Air Warfare Center's (NAWC's) Fleet Training Support Office, an investigation of this technique was undertaken to determine its legitimacy and to see if it were feasible to develop an experimental methodology to quantify and study the phenomenon in Fleet personnel, with an eye to improving Fleet personnel training.

FINDINGS

This preliminary study of the subject has resulted in startling new findings that transcend by a wide margin the most optimistic expectations of results conceivable at the commencement of the inquiry.

The findings of this experiment show that the Irlen phenomenon is real, that it is capable of being quantified, and that the Irlen treatment methodology is capable of altering the visual and cognitive performance of the dyslexic test subject to a significant extent.

Advanced analyses of the experimental results have shown a sound scientific basis for the Irlen phenomenon, based on the modern Receptor Field Theory of Human Vision.

This theory permitted the development of an experimental analytical model of the Irlen phenomenon that is capable of correlating the test subjects visual performance factors (such as reading speed) with receptor field energy states (in which correlation factors in the 0.8 to 0.9 range for the experimental data were attainable).

This experiment has provided startling new insight into the nature of the Irlen phenomenon, the base cause of dyslexia, and perhaps the very nature of human vision itself. This study's findings open up the possibility of effecting significant performance improvement for a portion of Fleet personnel, with minimum cost and effort.

SUMMARY OF EXPERIMENTAL RESULTS

This study used the "lay on" filter technique developed by Irlen, with formal quantitative data being taken on one test subject of the restricted vision span Irlen symptomalogy subgroup. Results of this base experiment show that

1. The Irlen effect is real. The energy spectrum presented to the eye of a dyslexic is capable of altering his or her visual and cognitive performance to a significant extent for both better and worse.

2. By varying the energy spectrum presented to eye of this dyslexic test subject, we were able to produce a reading speed variation ranging from 65% to 145% of normal.

3. This reading speed variation is not an independent variable, but is ultimately caused by changes in Angle of eye span and focal length. The angle eye span varies from 42% to 242% of normal and focal length varies over a range of 4.9 inches, which represents a change from 87% to 122.7% of normal.

4. The various subjective factors taken also showed a general correlation with reading speed, generally getting worse as reading speed deteriorated and better as reading speed improved.

Under the Receptor Field Theory of Human Color Vision, the cones of the eye are organized into a set of counter-balancing fields, with the balance output signal of the individual fields being the vision signal transmitted by the optic nerve to the brain for processing. If one reduces the energy spectrum presented to the test subject's eye by the filters into components corresponding to the individual cone dyes energy absorption responses and then feeds these data into a mathematical model of the receptor field system, one is capable of simulating the output signals of the test subject's vision system to the brain's visual processing center. If the data from this experiment are analyzed within the framework of the modern Receptor Field Theory of Human Vision in this manner, the data correlate to a remarkable extent, with the following results:

1. The data set for this test subject divides into three groups based on the energy domain of light reaching the eye. These energy domain groups act in a coherent manner among themselves, obeying their own internal rules of performance.

2. The quantifiable performance factors (reading speed, angle of eye span and focal length) vary within their domain groups based on their energy level within a given receptor field. These correlation factors run in the 0.8 to 0.9 range for reading speed and angle of eye span.

3. It appears that one receptor field is performance governing for any given domain group, with different receptor fields controlling performance in different spectral energy input regions.

4. Generally, visual performance improves within a governing receptor field as the energy level approaches zero or null from one side.

5. The behavior of the different performance factors appears to be entirely different on the positive and negative sides of a receptor fields zero point (or null asymptote).

6. One gets better reading speed and angle of eye span performance as the focal length approaches its normal value.

7. The domain groupings appear to be the result of the spectral energy reaching the eye being in regions of color space bounded by a given set of receptor field null asymptotes.

8. It appears that, in this "Irlen type" dyslexic test subject, the receptor field system as a whole does not sum to unity, but that the individual receptor fields act independently. This is not in accordance with generally accepted Reflector Field Vision Theory, which has held that the sum total of the receptor fields outputs do sum to a unity in the brain's vision processing center.

9. The subjective performance factor data that were originally taken merely as background information correlate to a remarkable degree, when analyzed by the same receptor field method. This analysis produces essentially the same results—lower energy in the governing receptor field is better—with reasonably high correlation factors (considering the subjective nature of the data).

MILITARY IMPLICATIONS OF FINDINGS

This study, which verifies the existence of a new human-factor element that affects 10% to 20% of service personnel, has a number of implications affecting training, use, and performance of military service personnel. Areas of potential military impact include the following:

1. The original question asked by the NAWC Fleet Training Support Office sometime ago, whether this phenomenon could affect training efficiency of naval personal, can now be answered: yes. It would appear, based on this study, that 10% to 20% of naval personnel (probably concentrated in the low-end performers) could be helped to perform better by paying attention to their special needs regarding lighting and frequency response of the paper of printed matter used in training. This would very likely significantly improve the performance of this sub-

group of the training population at minimum cost and with no adverse effect on the majority of the training population.

2. In the 1950s the U.S. Air Force conducted an extensive study regarding whether pilots could see better through yellow visors (then popular) as opposed to clear ones (a subject of debate at the time) and concluded that in reality there was no difference. Better sight though the yellow visors was just an old wives' tail. Based on the findings of this study, we must conclude that the findings of the Air Force study were incorrect. Some limited finite subgroup of the population (of which this test subject would be one) would see better through yellow visors. Furthermore, based on the findings of this study and work done by Irlen, one could conclude that in all probability some 10% to 20% of the pilot population would probably see better and perform better if they were tested and provided with visors specifically matched to the characteristic of their individual receptor field system.

3. It would appear from the findings of this study that some significant portion of the Navy's personal would be able to perform operational tasks better and with higher efficiency if their lighting environment were attuned to their personal needs, although this might have to be done by the individual Irlen method.

4. The military services have traditionally been one of the leaders in screening personnel for physical and physiological attributes in order to place them in a work environment where their unique personal talents and capabilities can best be used. The testing procedure development by this study provides a new avenue for screening and selection for military personnel for placement in environments where their natural talents and abilities can be put to optimum use while avoiding assignment of personnel to those operational environments where their visual performance parameters would cause them to inherently perform badly, thus putting the mission, naval assets, and/or other personnel at risk.

5. The results of this study demonstrate that there is the possibility of significant improvement in the performance and efficiency of a sizable portion of naval service personnel (maybe 10% to 20%) through modification of the work environment lighting system in which they perform their duties. This probably could be done with relatively minor effort and at relatively low cost.

OBJECTIVE

The primary objective of this study was to quantify the effects of various optical spectral filters on a single individual with Scotopic Sensitivity Syndrome.

The secondary objective of this study was to investigate data gathering and analysis methodologies that might be useful in analyzing Scotopic Sensitivity Syndrome on a broader scale.

QUANTIFICATION STUDY

EXPERIMENTAL TECHNIQUE

In this experiment, the subject observed and read material through color transparencies of known optical properties. Observations of the subject and his performance were then recorded on the data sheet for each of the filters in the test series in a quantified manner (as described in the following paragraphs).

Equipment

The color filtration transparencies used for this initial test program were a set of 40 filters supplied by Edmunds Scientific Inc. (Catalog no. 170,683) with a set of corresponding optical spectral transmission curves supplied by the same company. These transmission curves are reproduced in Appendix A. Timing was done with an electronic stop watch, operated manually by the observer.

For the reading material, a single standard pocket novel was used. This was done because it was felt that uniform textual material of moderate complexity should be used throughout the test to prevent as much as possible influences caused by differences in subject matter complexity. The use of a single textual source also eliminated any variation that might be caused by type face, type size, or paper quality. The selection of the book was more or less arbitrary on the part of the test subject.

To eliminate the differences in the spectral properties and intensity of light as much as possible from affecting the test results (unless it was desired as part of the test series), an effort was made to keep as uniform a light field as possible.[1] The light used was provided by a Spot Lighter incandescent bulb (GE Spot Lighter, R-20 bulb, 50 watt).

Distances were measured with a standard engineering ruler, which was not in a calibration system and not traceable back to the National Bureau of Standards.

[1] As discussed at some length in the section on Sources of Variation, this lighting control was probably inadequate.

Data-Collection Form

The data from the observations were recorded on a special form developed for this test program (Figure 1). The form was designed to record the specific factors known to be of interest in the case of this observer at the beginning of the test series. This results in two known problems with the experimental design:

1. The data-collection methodology may not be applicable to the entire general population of scotopic-sensitive individuals, because it is too specifically tailored to the problems of a single subject. In designing the data form, a number of conditions known to exist in other scotopic-sensitivity syndrome-affected individuals were not included in the quantification matrix because they were not applicable to this test subject.

2. There is the very real possibility that something significant was not measured, because in the design of the data-collection system, done at the beginning of the experiment, that parameter was not perceived to be important and therefore it was not collected and recorded. This is a problem of all psychophysical observation tests of this type.

FILTER No.	BRIGHTNESS	CLARITY OF LETTERS	TINT COLOR VISIBLE	FLICKER RATING	SUSTAINABILITY OF FOCUS RATING	PERCEPTION RATING	FOCAL LENGTH	EYE SPAN IN LETTERS	TAPE DISTANCE	ANGLE OF EYE SPAN	ANGLE OF ZONE OF PERCEPTION	READING SPEED	COMMENTS
NONE													
801													
802													
804													
805													
806													
807													
809													
810													
811													
813													
815													
817													
818													
819													
821													
823													
825													
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850													
851													
855													
856													
857													
861													
866													
863													
871													
874													
877													
878													

FIGURE 1. Color Test Data Form.

Data-Collection Form Definitions

The subject data form contains a number of categories and terms that have specific meanings in this experiment, some specifically derived for use in it. In addition, to attempt to quantify a number of the variables involved, a definitive scale for the event had to be established. This was often done somewhat arbitrarily in a finite range to facilitate quantification. For the purposes of this test series, the variables of the data-collection form are defined and quantified as follows:

1. **Filter No**. This number in the Edmund Scientific catalog is the number of the filter transparency used in the test; the number corresponds to the filter's published spectral transmission curves, shown in Appendix A.

2. **Brightness**. Brightness, in effect, means blackness. It was noted in some preliminary studies that under some filters the letters appeared blacker to the observer then they did under normal light, while under other filters, the letters appeared to be grayer. To attempt to quantify this, an arbitrary scale was set up with 0 representing the shade of blackness of the letters under normal light; +5 is the "blackest" lettering produced by any of the filters and -5 represents the "lightest" shade of gray seen. It was felt that the observer could distinguish a 20% difference up and down the scale.

3. **Clarity of Letters**. Clarity of letters refers to an attempt to quantify sharpness and fuzziness of letters as seen through the filters. Preliminary tests showed that under some filters, letters became sharper and more distinct, while others tended to appear fuzzy or screened (the term screened refers here to an effect similar to a photographic screen of the type used in print photography that produces a non-continuous image made up of dots). In this scale 0 was assigned as normal with 20% increments predefined up to the sharpest image given at +5 and down to a -5 for the fuzziest image.

4. **Tint Color Visible**. There appears to be some difference in the subject's color perception using reflected light through the filter transparencies as opposed to viewing the color as transmitted light through the filter itself. This column records whether the test subject sees a significant degree of color tint when viewing transmitted light through the filter.

5. **Flicker Rating**. For this test subject under normal light, all white-page printed material tends to move or flicker at some distances from the point of eye focus. It was found in preliminary tests that most color transparencies tend to reduce this to some extent. To attempt to quantify this, a scale of 0 to 5 was established with 0 being the normal white standard, progressing to 5 for the best expected.

6. **Sustainability of Focus Rating.** The subject found it easier to maintain eye focus looking through some transparencies as opposed to other transparencies. By the same token, some transparencies appeared to impair the ability to sustain focus. To attempt to quantify this, an open-ended scale was established, with 0 representing the normal white standard. Positive denoted better and negative worse.

7. **Perception Rating.** Some transparencies seem to cause the subject more difficulty when trying to perceive letters and words through them than other transparencies. This difficulty may result from two distinct causes: (1) a mental imaging defect may be occurring at some light frequency, which is probably connected with the root cause of Scotopic Sensitivity Syndrome, and (2) the color tint may be too dark, thereby reducing the contrast to the point where the subject has trouble distinguishing the letters. The latter is a quite normal problem. How to distinguish between the two effects in this test was not known. Therefore, a gross rating covering the two factors was established to attempt to quantify the difficulty of perception through the filters. This was set up on a bases of 0 at normal white and extending to ±5, plus being better perception, minus being worse.

8. **Focal Length.** It was noted in preliminary tests that the distance at which it was comfortable to read changed slightly depending on the color of the transparency the test subject was looking through. To attempt to quantify this change and supply data for calculating the angle of eye span, a measurement was taken with a collapsible rod, the length of which was then measured using an engineering scale. The measurements were recorded in inches.

9. **Eye Span.** Eye span was measured by the test subject both in terms of letters seen and a dotted tape. Measurement on the tape was taken by a caliper and measured on an engineering scale. The readings were recorded in inches.

10. **Angle of Eye Span.** The angle of eye span was calculated using the inch measured eye span from the dotted tape and the focal length measurement. The angle should be considered to be relative rather than absolute, since the focal length measurement was taken from a point on the tip of the nose rather than the surface of the eye. This was done simply as a matter of testing expediency.

QUANTIFICATION STUDY TEST RESULTS

The results of the quantification study tests are presented in Table 1.

Analysis of Quantification Test Results

Analysis of the raw test data results of Table 1 shows that for this observer the following apply:

1. Irlen is correct, that in this subject, the ability to read does alter significantly when various color frequency modifications are presented to the test subject's eyes (Figure 2). In fact, the reading speed of the test subject varies from 65% to 145% of normal, depending on the filter used (Figure 3).

2. The data also show that Irlen is correct, that some color filters make the problem worse rather than better. In fact, some 18 of the filters tried on this subject did decrease reading speed as opposed to 14 filters that improved it.

3. The fact that reading speed varies both positively and negatively over the assorted color range used indicates that more complicated phenomena than just reduction of light level is going on.

4. The analysis of the raw data shows that there is an altering of the zone of perception (as measured by angle of eye span) under various color filter conditions (see Table 1). Further analysis shows that there is a relatively high correlation coefficient between eye span and reading speed (Figures 4 through 6), the correlation coefficients being 0.672, 0.658, and 0.642 respectively. The same is true for the more complicated angle of eye span calculation results, which show a similar correlation (Figure 7). In fact, the correlation data would indicate that it is an angle of eye span (or the zone of presentation) that counts and correlates best with increased reading speed (see Figure 4), the factor has a correlation coefficient of 0.6935.

TABLE 1. Color Test Data.

FILTER No.	BRIGHTNESS	CLARITY OF LETTERS	TINT COLOR VISIBLE	FLICKER RATING	SUSTAINABILITY OF FOCUS RATING	PERCEPTION RATING	FOCAL LENGTH	EYE SPAN IN LETTERS	EYE SPAN IN TAPE DISTANCE	ANGLE OF EYE SPAN	ANGLE OF EYE SPAN INCREASE AS % OF NORMAL	READING SPEED	READING SPEED AS % OF NORMAL	COMMENTS
NONE	0	0	NO	0	0	0	14.125	3	0.300	1.22	100.00%	2:32	100.00%	
801	+1	+1	NO	0	0	+1	13.875	5	0.450	1.86	152.71%	2:22	93.42%	
802	+1	+2	YES	+2	+2	+1	14.7	6	0.625	2.44	200.20%	1:53	134.51%	
804	+2	+2	NO	+1	+1	+2	14.1	8	0.725	2.95	242.12%	1:45	144.76%	
805	+3	+3	YES	+2	+2	+2	15.2	8	0.750	2.83	232.34%	2:10	116.92%	
806	+2	-1	YES	0	+1	-1	14.2	3	0.325	1.31	107.76%	2:46	91.57%	
807	-1	+1	YES	+2	0	0	12.7	2.5	0.250	1.13	92.68%	2:42	93.83%	
809	+1	+1	YES	+1	+1	0	14	3.5	0.300	1.23	100.89%	2:58	85.39%	
810	+1	0	YES	+1	+1	0	13.4	2.5	0.250	1.07	87.84%	2:42	93.83%	
811	+1	+2	YES	+1	+2	+2	14.6	4.5	0.450	1.77	145.12%	2:19	109.35%	
813	0	+1	YES	+1	0	0	15	5	0.500	1.91	156.95%	2:47	91.02%	
815	+2	+2	YES	+1	+1	+2	14.2	3.5	0.250	1.01	82.89%	2:28	102.70%	
817	+1	-1	YES	+1	-1	0	13.75	3	0.250	1.04	85.61%	2:28	102.70%	
818	0	+1	YES	+1	-2	-1	13.2	2.5	0.200	0.87	71.34%	2:40	95.00%	
819	-1	+1	YES	+1	-2	-2	14.1	2	0.175	0.71	58.44%	2:45	92.12%	
821	-5	-5	YES	- -	- -	- -	19.8	- -	- -			- -	- -	TOO DARK TO READ
823	-5	-5	YES	- -	- -	- -	- -	- -	- -			- -	- -	TOO DARK TO READ
825	-1	0	YES	+1	-2	+1	17.2	2.5	0.175	0.58	47.90%	2:51	88.89%	
826	+1	+1	YES	+2	0	0	15.2	3.25	0.275	1.04	85.18%	2:40	95.00%	
828	+1	-1	YES	+1	-2	0	15.2	2.5	0.175	0.66	54.21%	2:45	92.12%	
830	-1	+1	YES	0	-1	-1	16.375	3	0.275	0.96	79.07%	2:44	92.68%	
832	-2	-2	YES	0	-2	-2	17	2	0.150	0.51	41.54%	3:53	65.24%	ALMOST TOO DARK TO READ
834	+1	+1	YES	0	-1	-1	14.375	3.25	0.275	1.10	90.07%	2:29	102.01%	
837	-2	-2	YES	0	-2	-2	16.3	4	0.375	1.32	108.32%	3:06	81.72%	
838						-4						- -	- -	UNREADABLE
839						-5						- -	- -	UNREADABLE
841	-2	-1	YES	0	-2	-2	15	4	0.350	1.34	109.86%	2:28	102.70%	
842	-2	-1	YES	+1	-2	-2	15.75	3	0.200	0.73	59.79%	2:36	97.44%	
843						-4						- -	- -	UNREADABLE
846						-5						- -	- -	UNREADABLE
849	+2	+2	YES	+2	+2	+2	15.375	5	0.550	2.05	168.43%	2:14	113.43%	
850	-1	-1	YES	+1	-1	-1	15.375	4	0.350	1.30	107.18%	2:27	103.40%	
851	-1	-2	YES	+1	-1	-1	13.5	3.5	0.300	1.27	104.63%	2:01	125.62%	
855	-1	-1	YES	+2	-1	+1	14.1	5.5	0.550	2.24	183.67%	2:24	105.56%	
856	-2	-2	YES	+1	-1	-1	13.25	2.5	0.175	0.76	62.18%	2:16	111.76%	
857	-3	-2	YES	+1	-1	-2	12.3	3	0.200	0.93	76.56%	2:38	96.20%	TOO DARK
858	-1	+1	YES	+1	+1	+1	13.875	4.5	0.375	1.55	127.25%	2:40	95.00%	
861							11.3					- -	- -	TOO DARK TO READ
866												- -	- -	UNREADABLE
863												- -	- -	UNREADABLE
871	-1	+1	YES	+1	+1	+1	13.4	4.5	0.350	1.50	122.98%	2:40	95.00%	
874	-3	-1	YES				12.1	2.5	0.175	0.83	68.10%	- -	- -	TOO DARK TO READ
877												- -	- -	UNREADABLE
878	+3	+2	YES	+1	+2	+2	14.375	5	0.500	1.99	163.77%	2:20	108.57%	

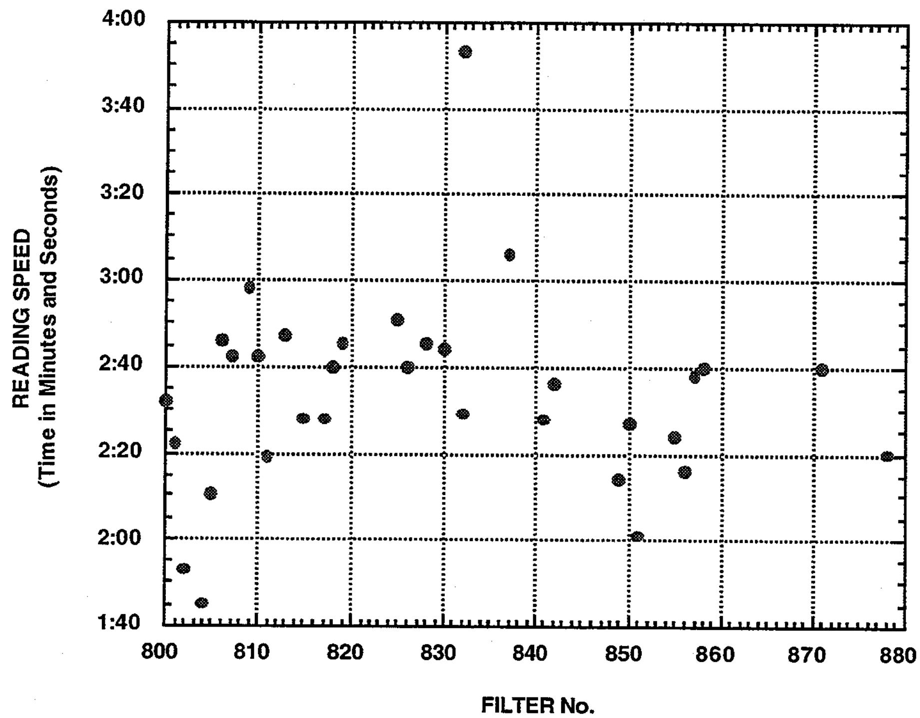


FIGURE 2. Reading Speed for Filters.

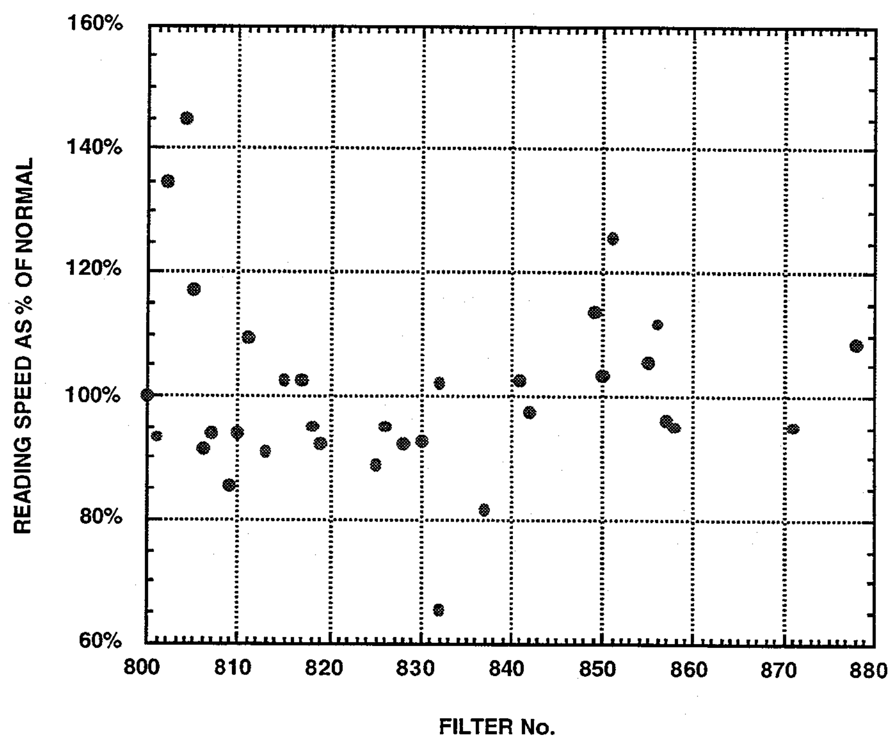


FIGURE 3. Reading Speed as Percentage of Normal

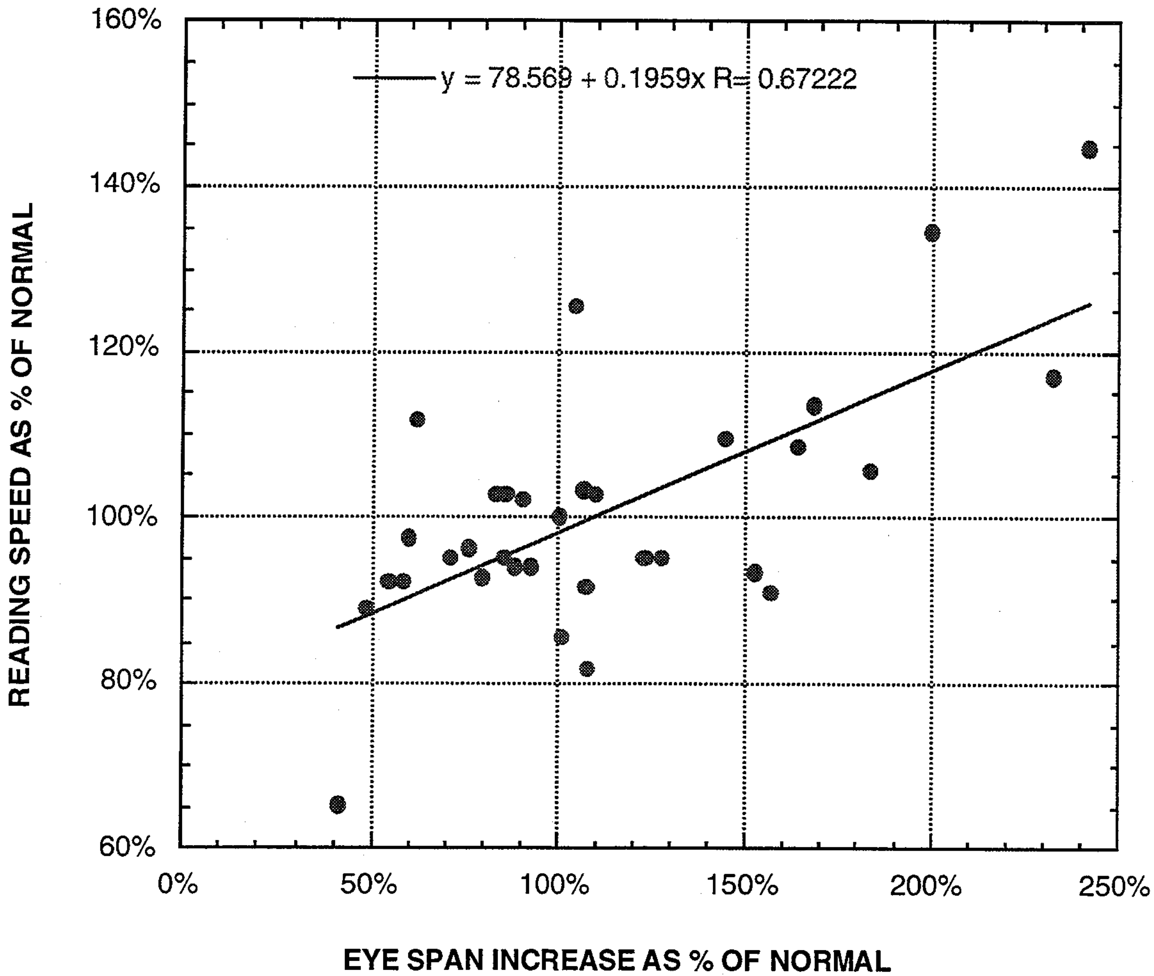


FIGURE 4. Eye Span vs. Reading Speed.

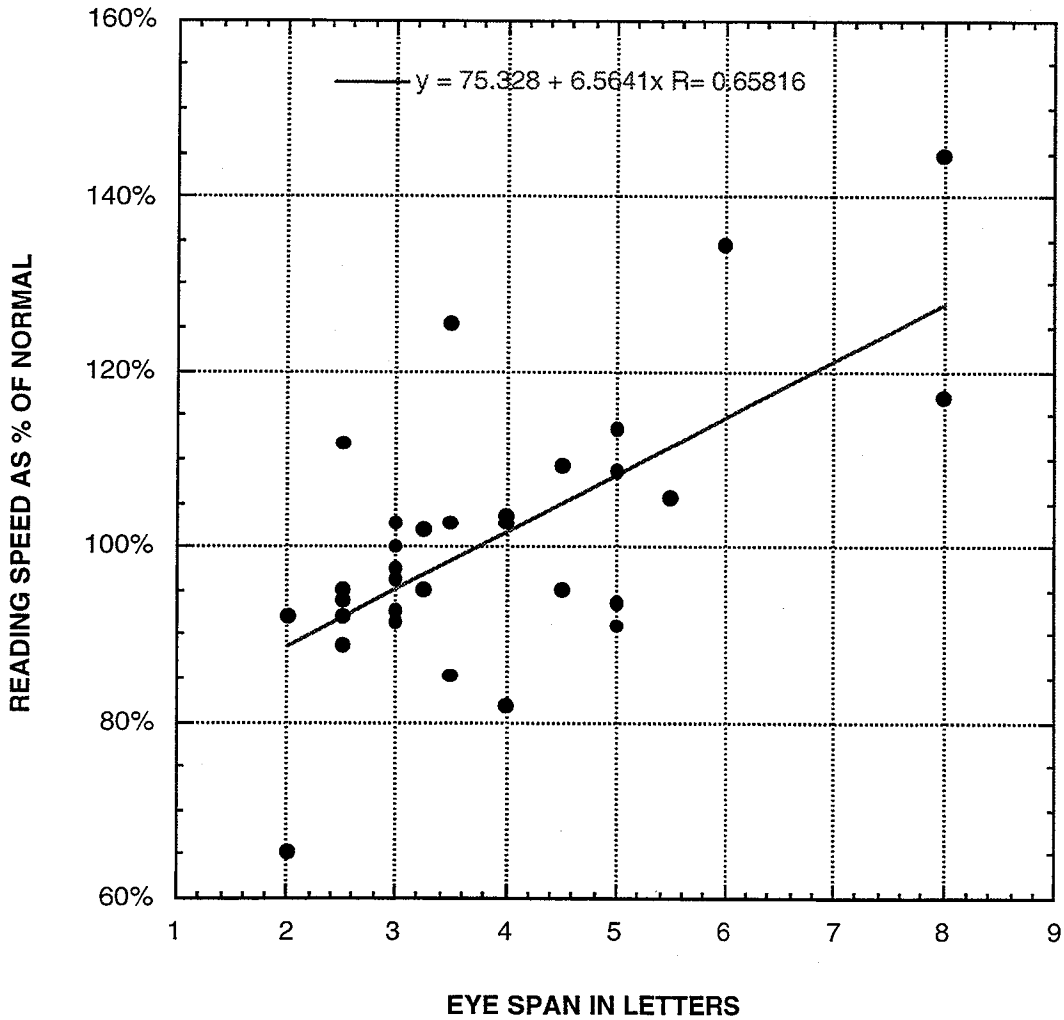


FIGURE 5. Eye Span in Letters vs. Reading Speed.

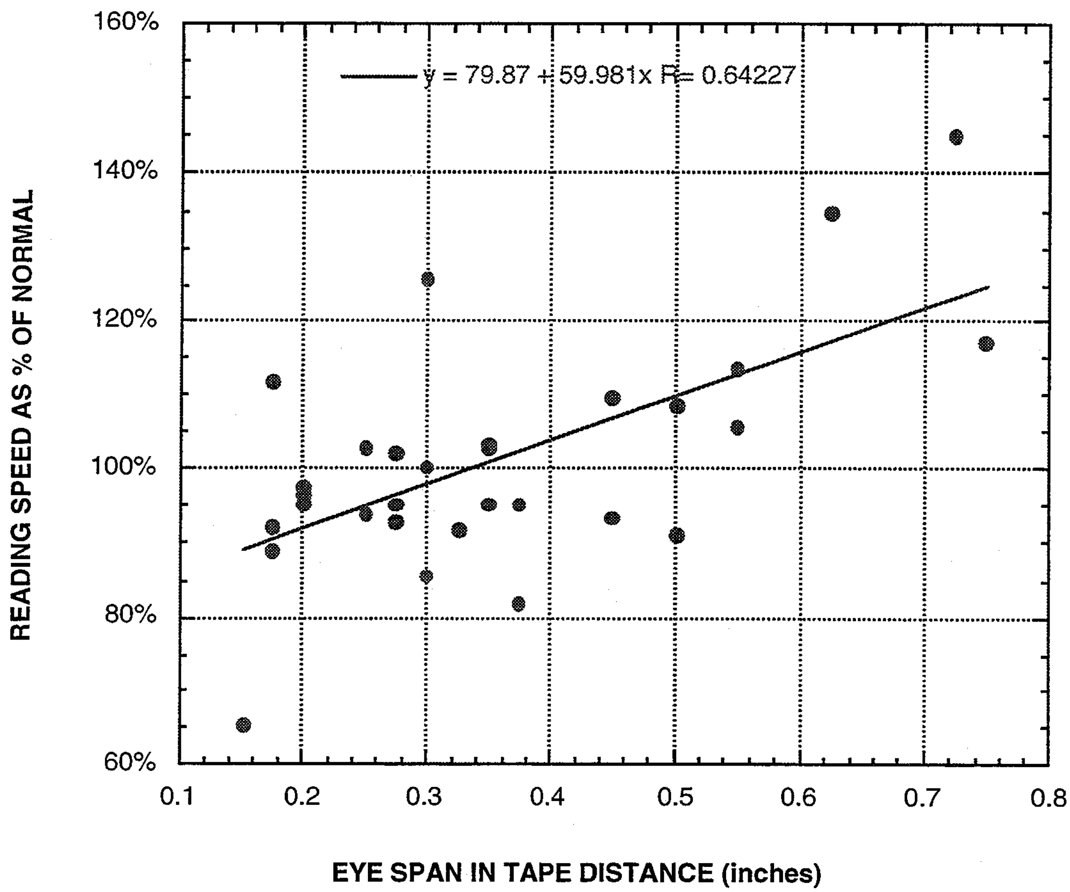


FIGURE 6. Eye Span Distance vs. Reading Speed.

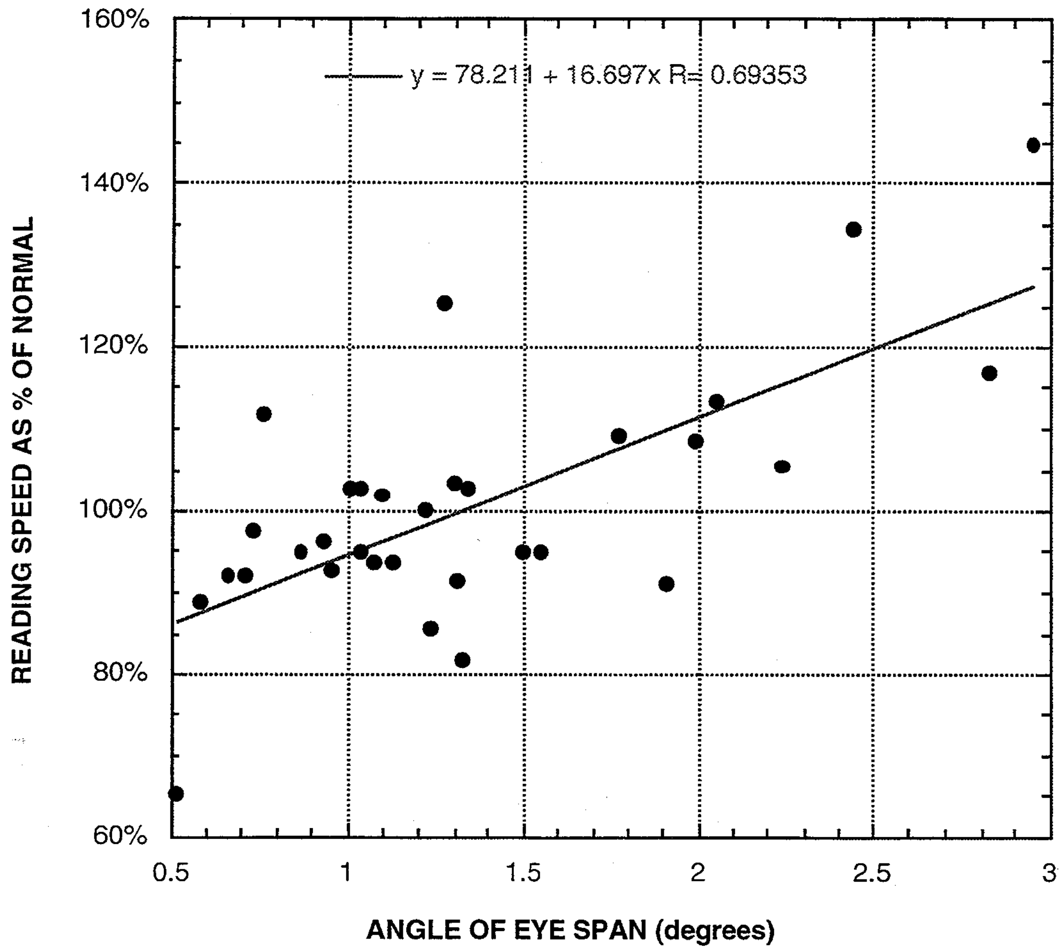


FIGURE 7. Angle of Eye Span vs. Reading Speed.

5. Analysis of the various subjective factors was also conducted as a matter of interest. While the subjective factors lack real precision, they all show positive coefficients of correlation ranging from 0.35 to 0.47 between reading speed and improvement in their individual factor. [2] These factors, as shown in Figures 8 through 12, however, appear to be of minor significance for this subject and do not appear to have a major. These data are presented for each of the factors as follows:

Factor	Figure
Flicker rate	8
Perception rating	9
Clarity of letters	10
Brightness	11
Sustainability of focus	12

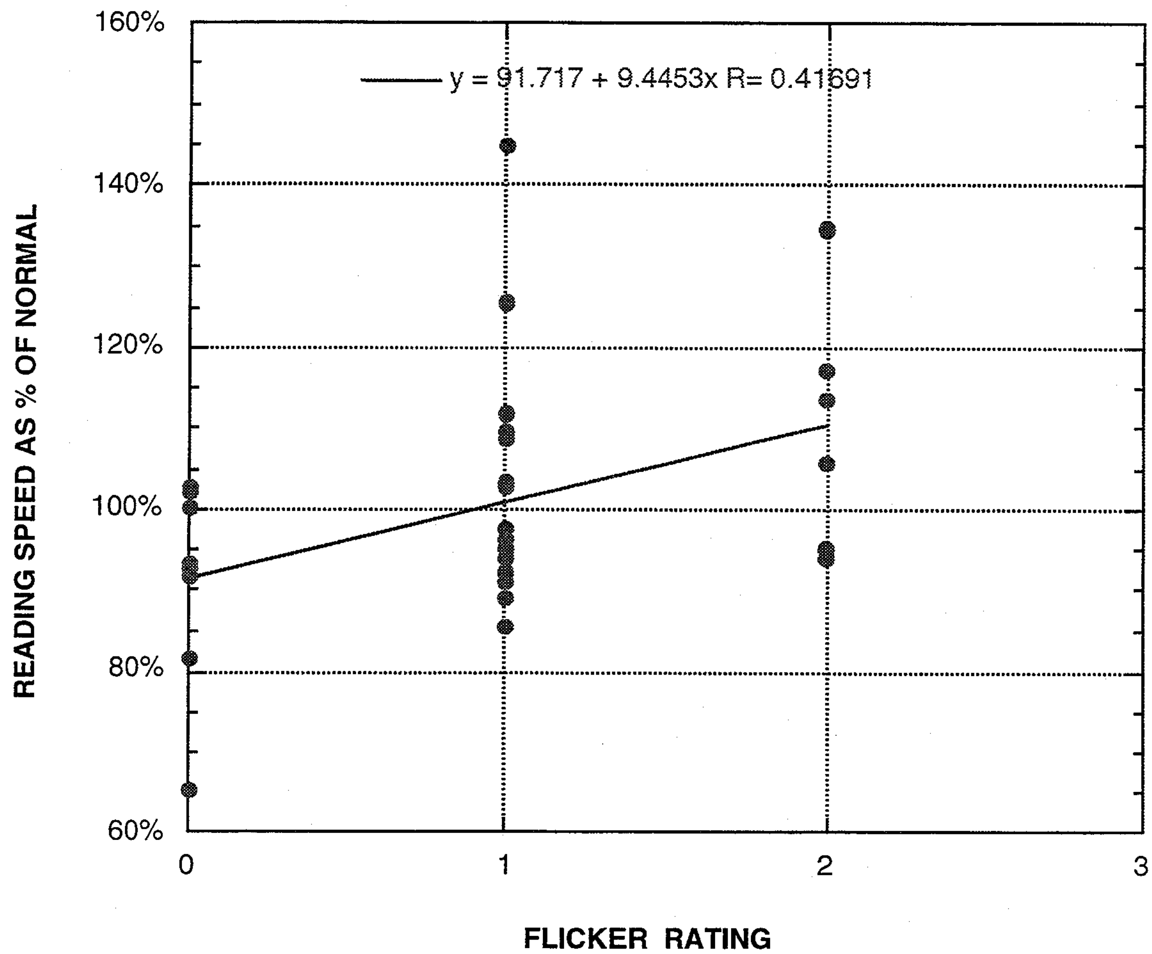


FIGURE 8. Flicker Rating vs. Reading Speed.

[2] It should be noted that if one does a curve fit analysis on these data, one finds that a two factor polynomial generally produces a better fit and a slightly higher correlation factor.

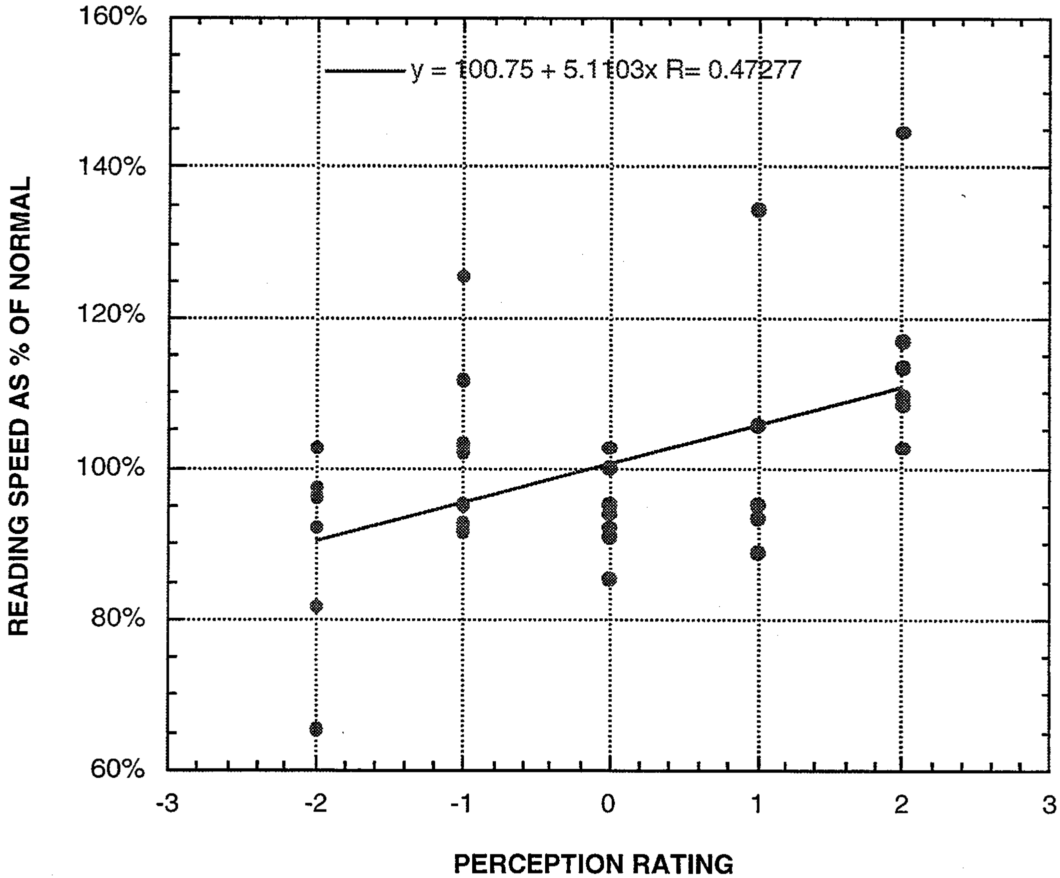


FIGURE 9. Perception Rating vs. Reading Speed.

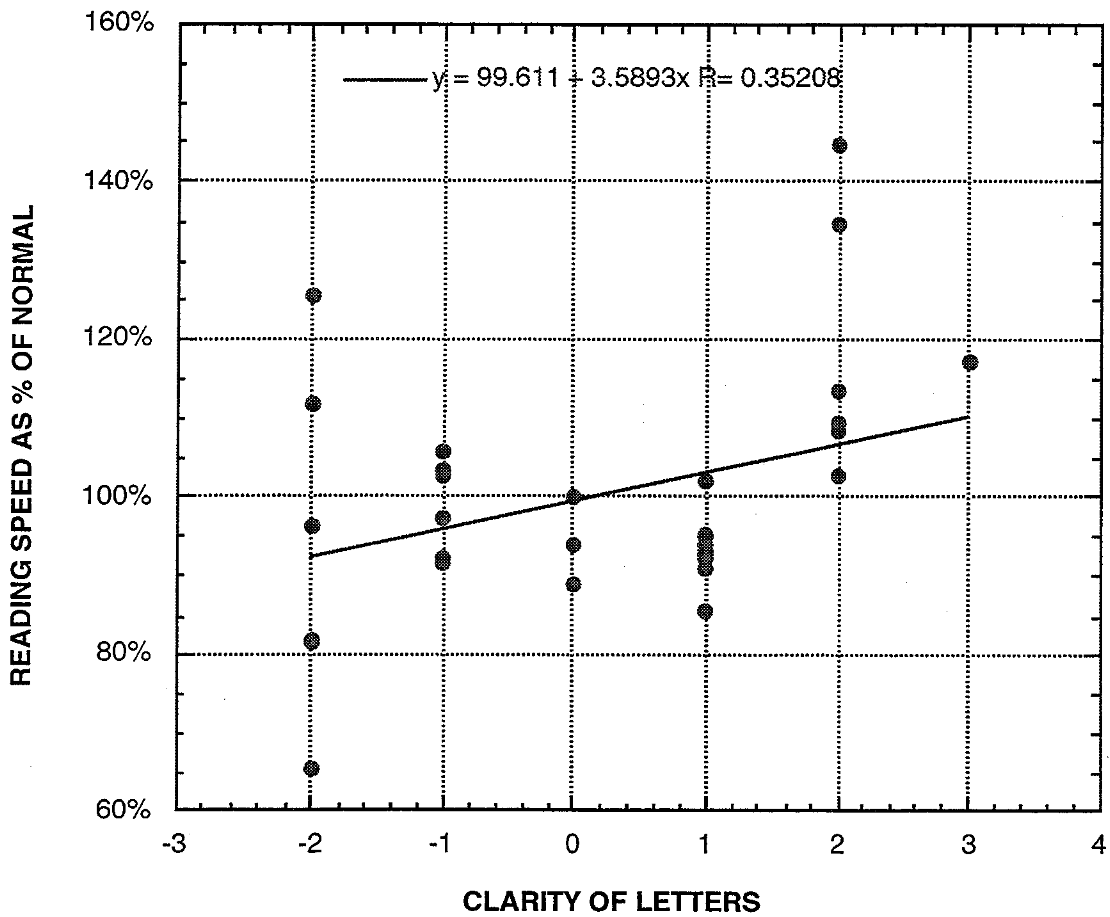


FIGURE 10. Clarity of Letters vs. Reading Speed.

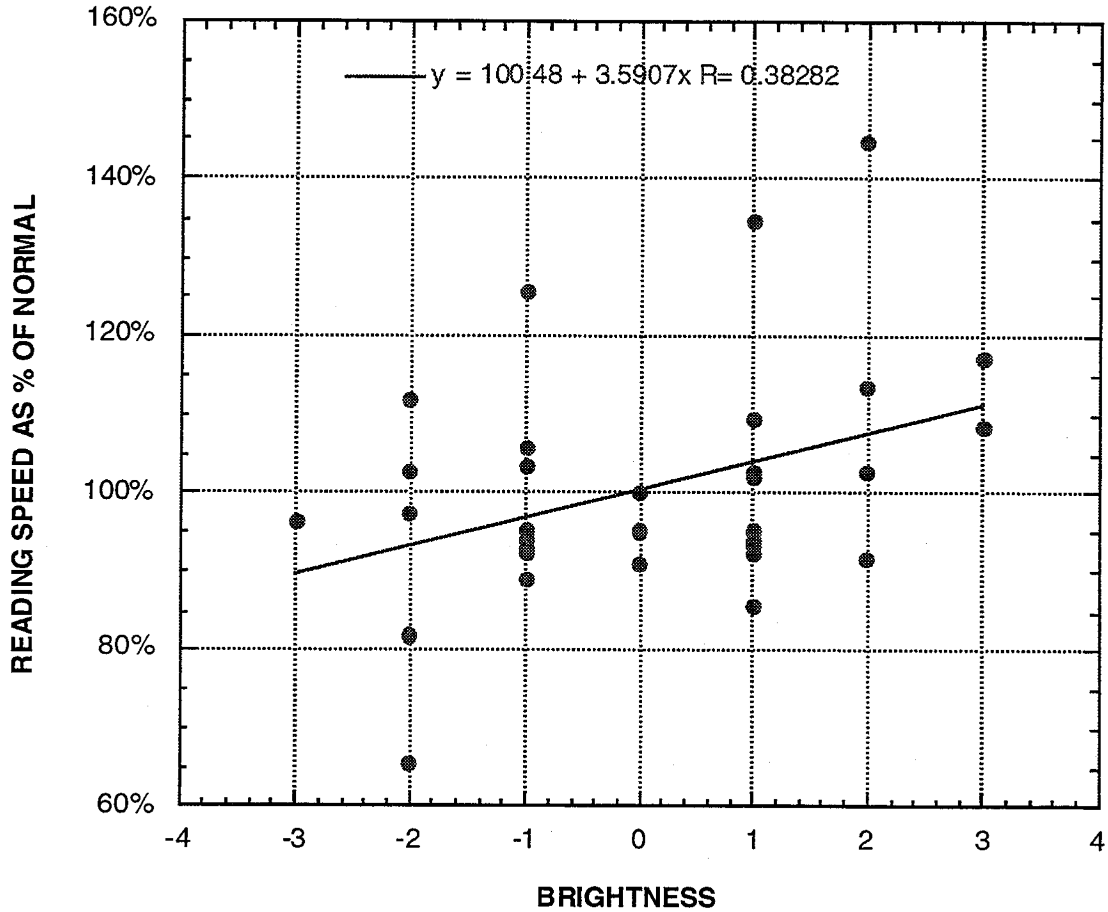


FIGURE 11. Brightness vs. Reading Speed.

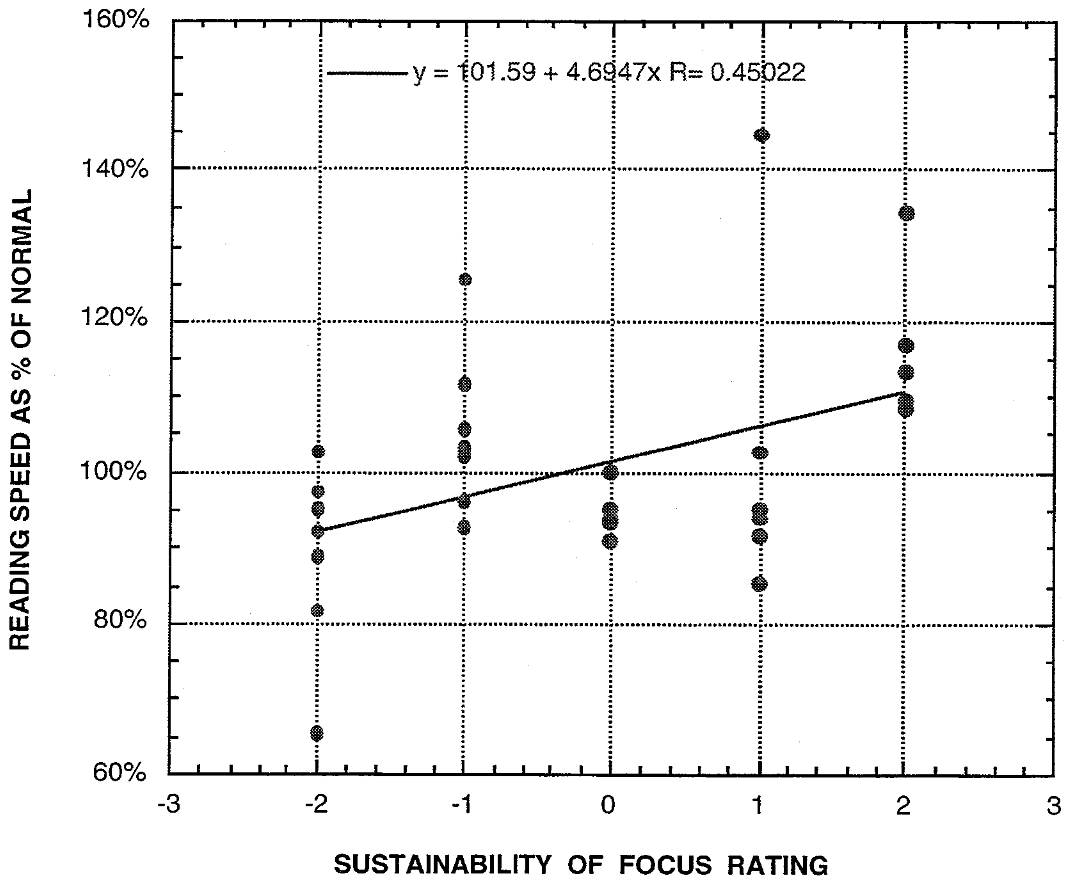


FIGURE 12. Sustainability vs. Reading Speed.

6. By the same token, if one graphs the various subjective factors against each other, one finds that there is a general rudimentary correlation of improvement between most of them, the exception being flicker, which does not seem to correlate with much of anything (Figures 13 though 22).

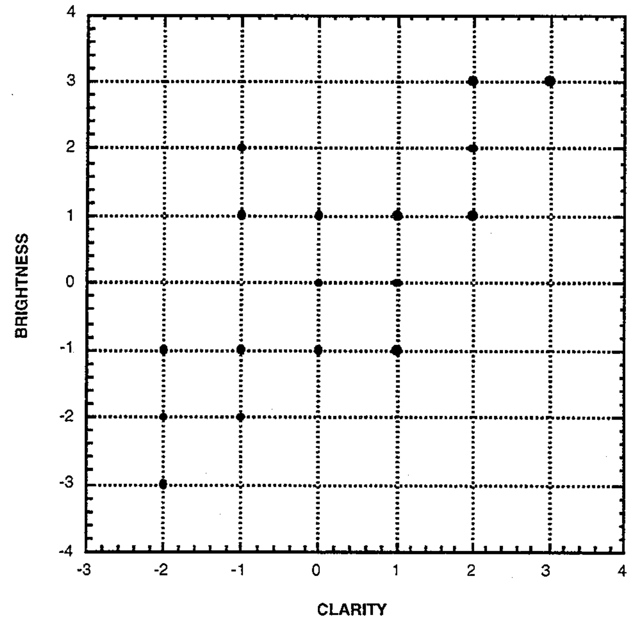


FIGURE 13. Brightness vs. Clarity.

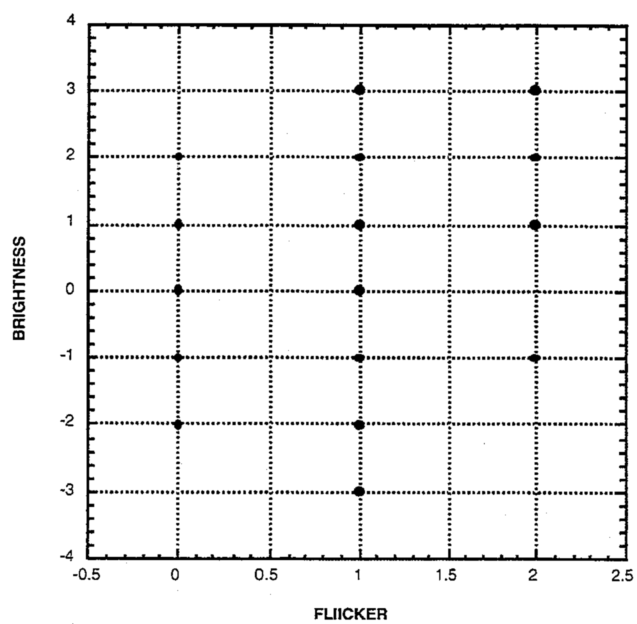


FIGURE 14. Brightness vs. Flicker.

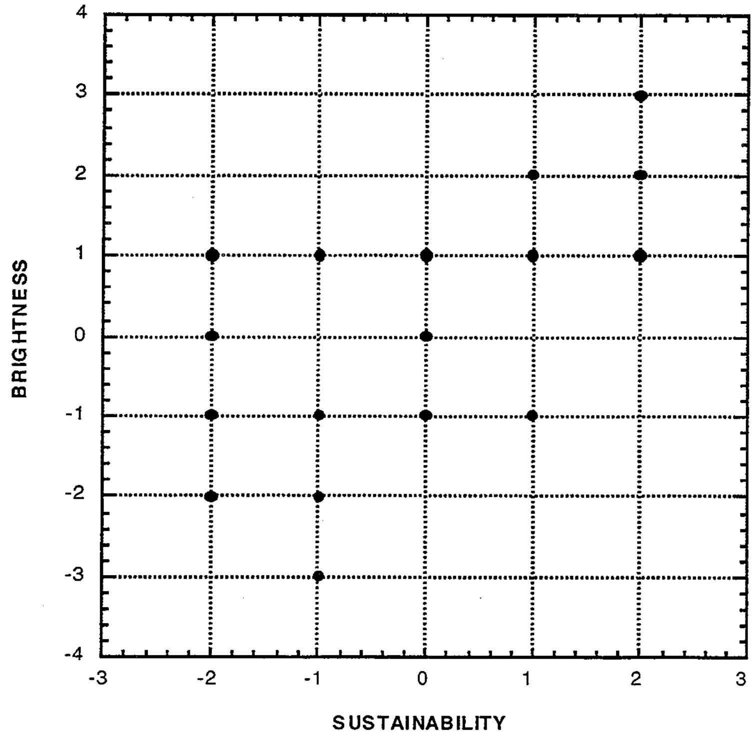


FIGURE 15. Brightness vs. Sustainability.

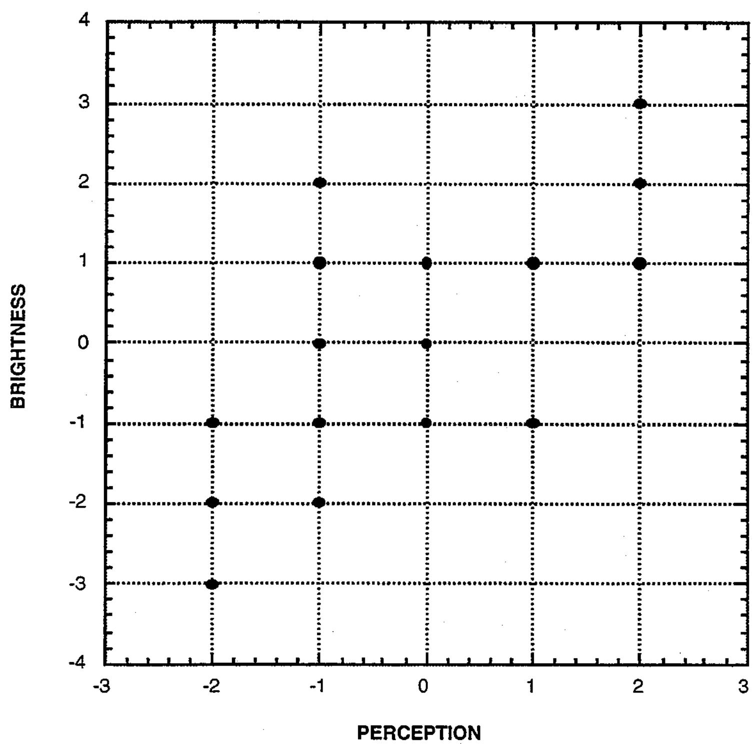


FIGURE 16. Brightness vs. Perception.

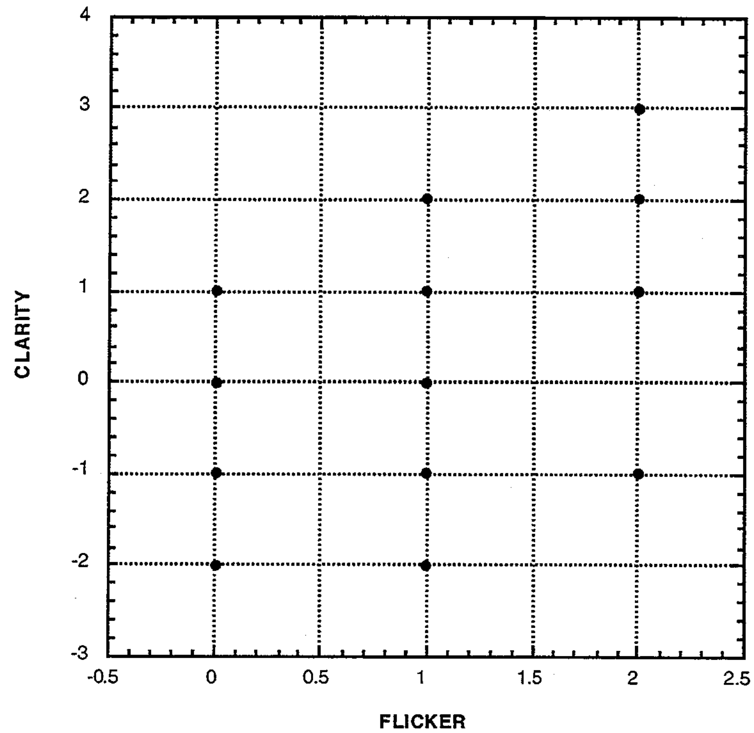


FIGURE 17. Clarity vs. Flicker.

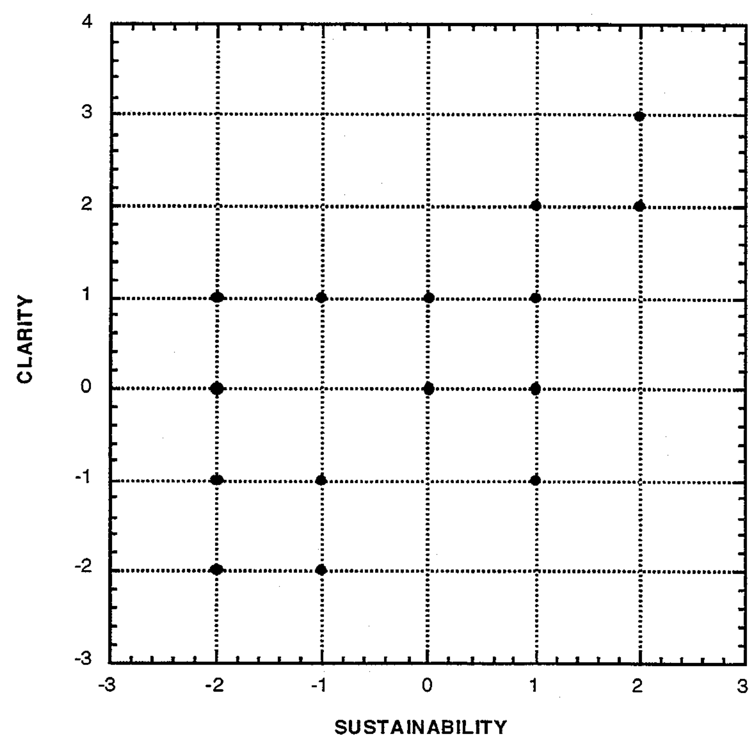


FIGURE 18. Clarity vs. Sustainability.

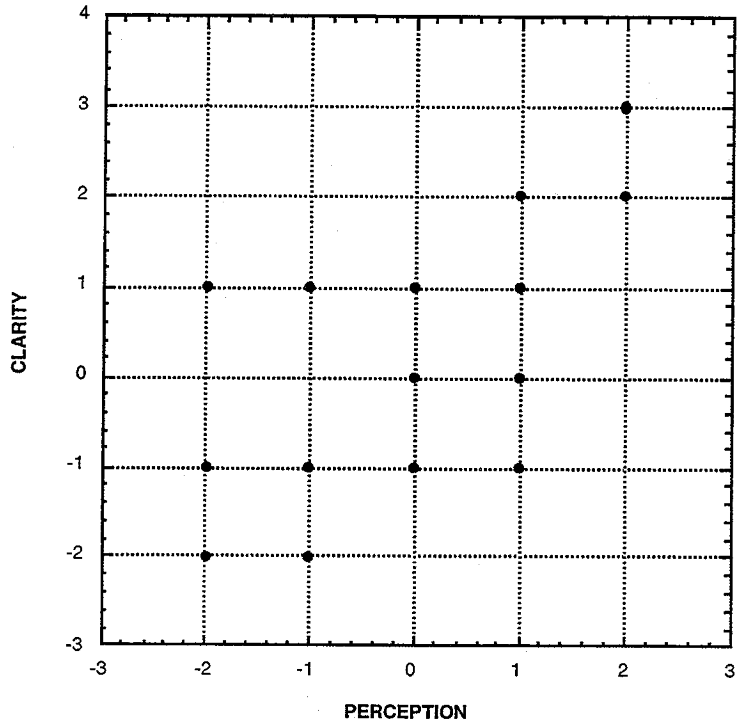


FIGURE 19. Clarity vs. Perception.

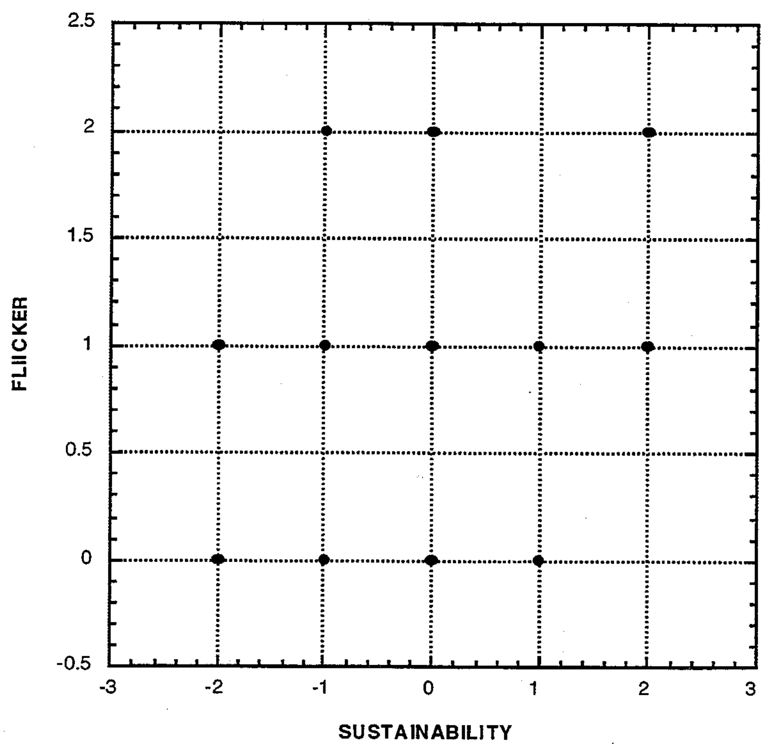


FIGURE 20. Flicker vs. Sustainability.

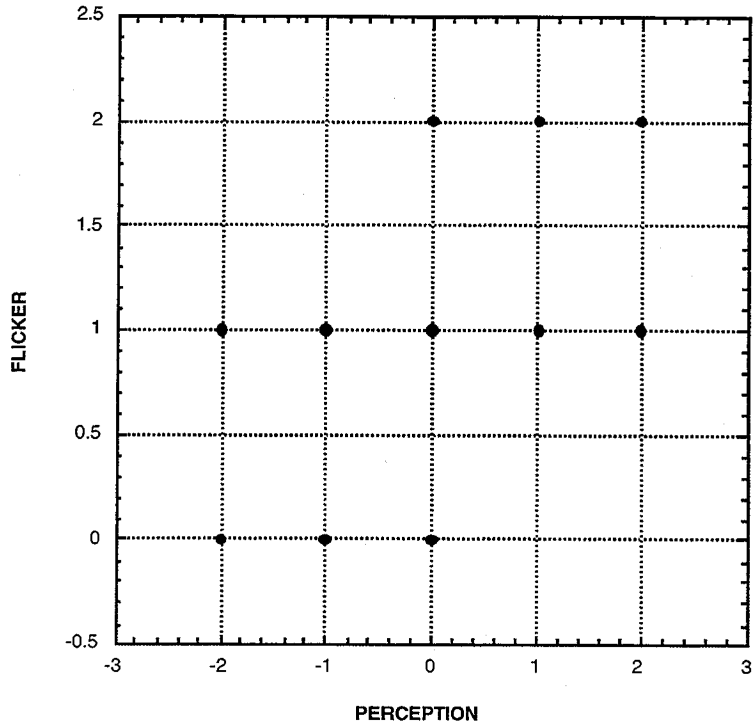


FIGURE 21. Flicker vs. Perception.

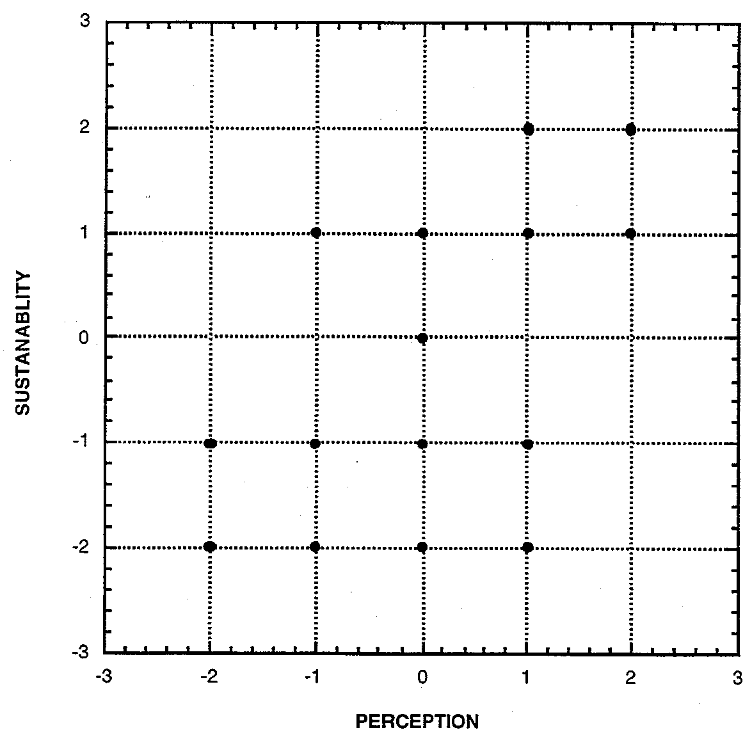


FIGURE 22. Sustainability vs. Perception.

7. The focal length of the test subject's eyes changed over a range of 4.9 inches (34.69%) when he read through various filters moving from 12.3 to 17.2 inches (with 14.125 inches being normal in white light), with the greatest increase being 3.075 inches above normal (21.77%) and the low -1.825 inches below normal (-12.92%). This variance of focal length was an unexpected phenomenon and was graphed against reading speed. This graph showed a somewhat confusing pattern that would lead one to conclude that there may be more than one homogeneous set of data represented in the data set on the graph (Figure 23). [3]

8. If, on the other hand, one graphs the absolute focal length change in ascending order, one sees that the focal length varies widely around the nominative normal focal length of 14.125 inches (Figure 24).

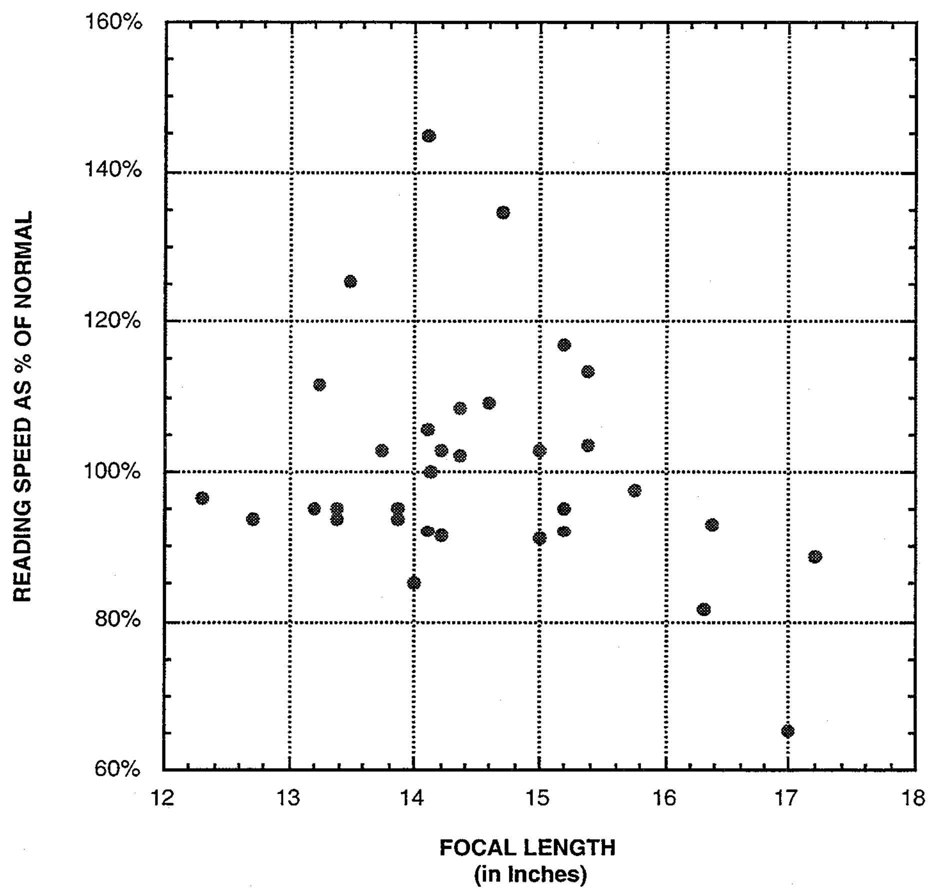


FIGURE 23. Focal Length vs. Reading Speed.

[3] Subsequent analysis shows that this is in fact the case.

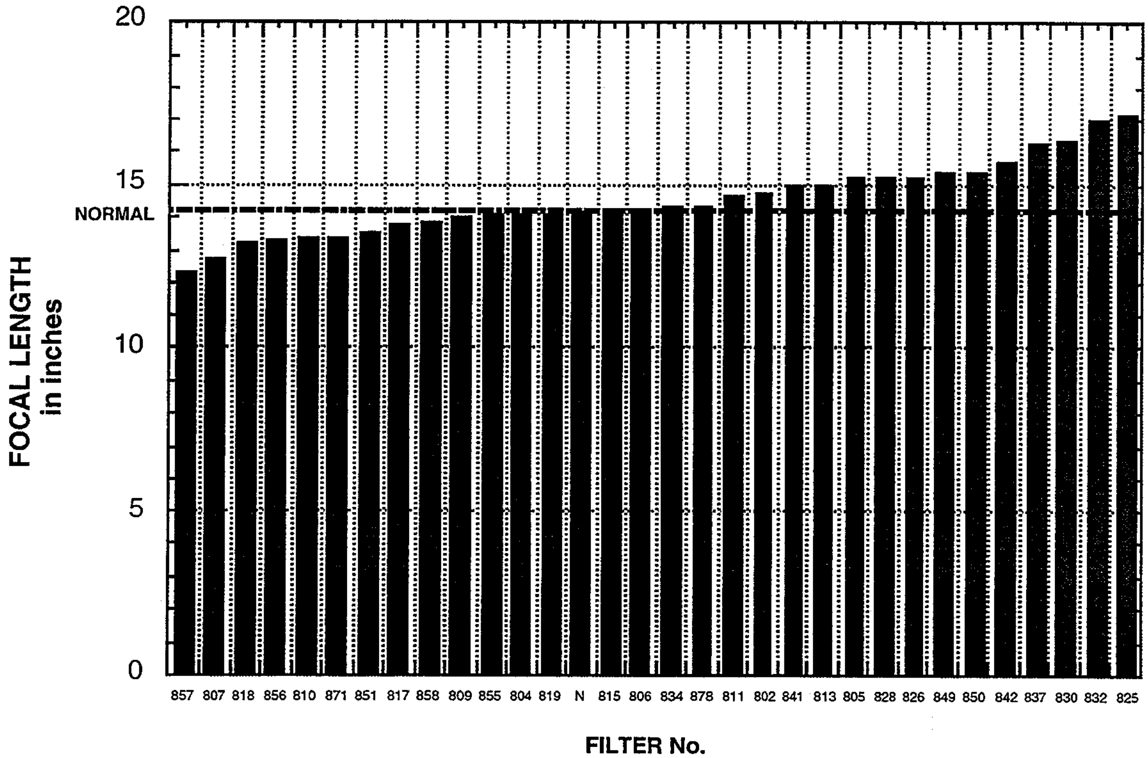


FIGURE 24. Focal Length.

9. The calculated angle of eye span is a combination of focal length and eye span changed from its normal 1.1217 by + 1.729 degrees to - 0.637 degrees, a range of 2.366 degrees. This represents a change of 194.46% (+142% to -52%) from normal size. The relationship between angle of eye span and focal length is shown in Figure 25. The correlation of reading speed with the angle of eye span is shown in Figure 7.

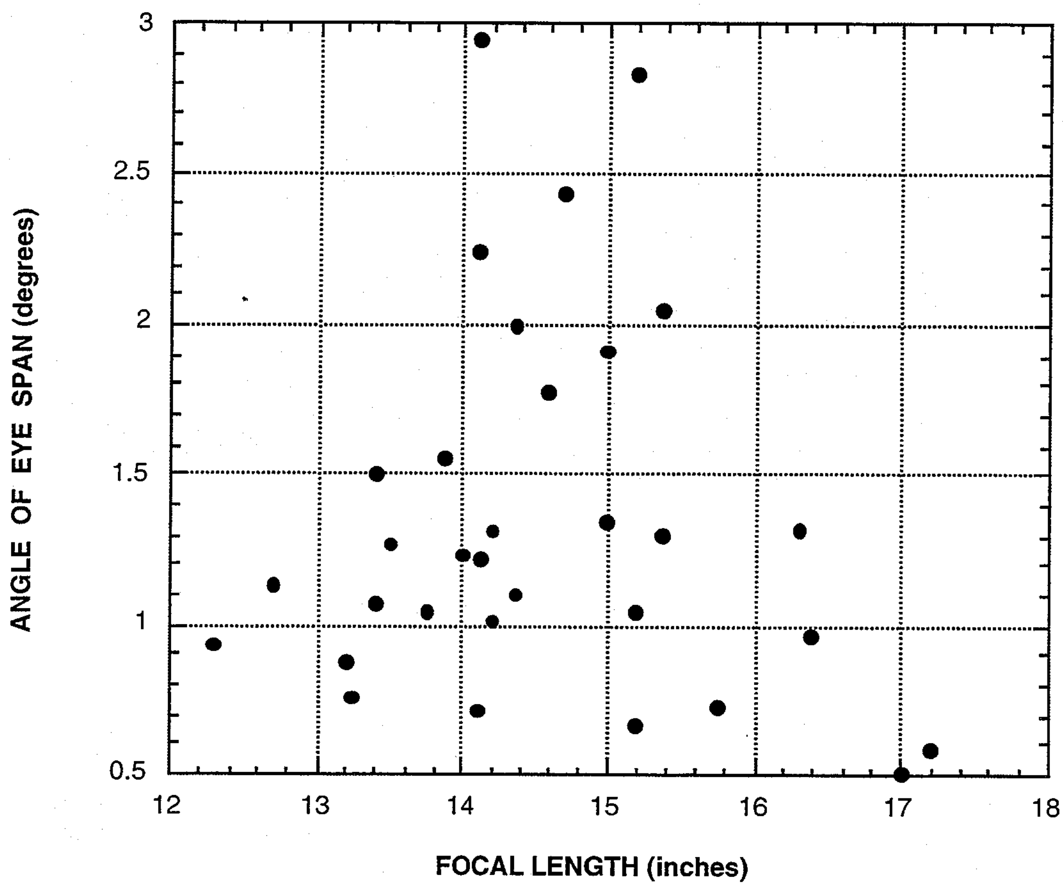


FIGURE 25. Angle of Eye Span vs. Focal Length.

The quantitative and percentage change of focal length, tape distance and angle of eye span are shown in Table 2 for the maximum and minimum conditions and for the individual cases in Table 3. The individual tested here belonged to the restricted eye span subgroup of the Irlen symptomalogy.

This sub-group has a vision pattern that can be divided into three distinct zones. These are shown on the Vision Zone Diagram, Figure 26. In this subgroup, the individual has a very small active mental image zone, usually only several letters and sometimes smaller. In this test subject's case, the active mental image zone is only about three letters (actual measured eye span under normal light was 0.300 inch). In this subject's case, the active mental image zone was calculated to represent a vision span of only 1.22 degrees under normal light.

Beyond this is a much larger area called the zone of perception in which the individual can tell that there are letters and words, but these are sort of fuzzy and the individual cannot really read them. Beyond this is the zone of cognizance in which the individual can discern blurry blocks of something, but there is insufficient detail for him or her to perceive them as either letters or words. A representation of what the individual sees is shown in Figure 27, which is how this individual perceives the letter of Figure 28, if he or she stares at the letter e in the word secured.

Under the influences of the best filter, the zone of active mental image increases from 1.22 to 2.95 degrees (with a resultant increase of reading speed to 142% of normal). It was also reported by the test subject that two other phenomena occur:

1. The zone of perception expanded significantly.

2. It was easier to move his eye across the line of print.

Under some filters, the eye span angle and its associated zone of mental image drop significantly (down to less than three-quarters of a degree) and the subject reported that it became very difficult to read or do anything else requiring visual imaging. Under the influence of some filters at the very fringes of readability it appeared that negative variation of the focal length and eye span was even greater, but quantifiable data to support this were not obtainable.

TABLE 2. Maximum-Minimum Focal Length and Angle of Eye Span.

Performance Factor	Measurement	Normal	High	Low	Total Range (Max. + Min.)	Range High	Range Low
Tape Distance	In inches	0.300	0.750	0.150	0.600	0.450	-0.150
	in %	100.00	250.00	50.00	200.00	150.00	-50.00
Focal Length	In inches	14.125	17.200	12.300	4.900	3.075	-1.825
	in %	100.00	121.77	87.08	34.69	21.77	-12.92
Angle of Eye Span	In degrees	1.217	2.946	0.506	2.441	1.729	-0.711
	in %	100.00	242.12	41.54	200.57	142.12	-58.46

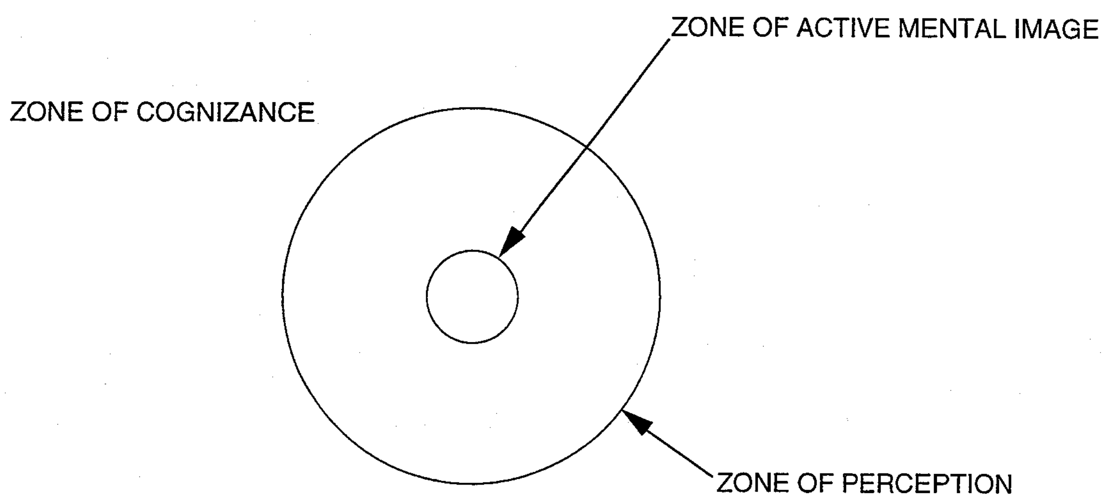


FIGURE 26. Vision Zone Diagram.

TABLE 3. Focal Length and Angle of Eye Span for Individual Cases.

FILTER No.	FOCAL LENGTH	EYE SPAN IN LETTERS	EYE SPAN IN TAPE DISTANCE	ANGLE OF EYE SPAN	ANGLE OF EYE SPAN INCREASE AS % OF NORMAL	READING SPEED	READING SPEED AS % OF NORMAL	COMMENTS	FOCAL LENGTH CHANGE FROM NORMAL (IN INCHES)	FOCAL LENGTH CHANGE FROM NORMAL (IN %)	VARIANCE OF FOCAL LENGTH (IN %)	EYE SPAN TAPE DISTANCE VARIATION	EYE SPAN TAPE DISTANCE VARIATION AS %
NONE	14.125	3	0.300	1.22	100.00%	2:32	100.00%		0	100.00%		0.00	0.00%
801	13.875	5	0.450	1.86	152.71%	2:22	93.42%		-0.25	98.23%	1.77%	0.150	50.00%
802	14.7	6	0.625	2.44	200.20%	1:53	134.51%		0.575	104.07%	-4.07%	0.325	108.33%
804	14.1	8	0.725	2.95	242.12%	1:45	144.76%		-0.025	99.82%	0.18%	0.425	141.67%
805	15.2	8	0.750	2.83	232.34%	2:10	116.92%		1.075	107.61%	-7.61%	0.450	150.00%
806	14.2	3	0.325	1.31	107.76%	2:46	91.57%		0.075	100.53%	-0.53%	0.025	8.33%
807	12.7	2.5	0.250	1.13	92.68%	2:42	93.83%		-1.425	89.91%	10.09%	-0.050	-16.67%
809	14	3.5	0.300	1.23	100.89%	2:58	85.39%		-0.125	99.12%	0.88%	0.000	0.00%
810	13.4	2.5	0.250	1.07	87.84%	2:42	93.83%		-0.725	94.87%	5.13%	-0.050	-16.67%
811	14.6	4.5	0.450	1.77	145.12%	2:19	109.35%		0.475	103.36%	-3.36%	0.150	50.00%
813	15	5	0.500	1.91	156.95%	2:47	91.02%		0.875	106.19%	-6.19%	0.200	66.67%
815	14.2	3.5	0.250	1.01	82.89%	2:28	102.70%		0.075	100.53%	-0.53%	-0.050	-16.67%
817	13.75	3	0.250	1.04	85.61%	2:28	102.70%		-0.375	97.35%	2.65%	-0.050	-16.67%
818	13.2	2.5	0.200	0.87	71.34%	2:40	95.00%		-0.925	93.45%	6.55%	-0.100	-33.33%
819	14.1	2	0.175	0.71	58.44%	2:45	92.12%		-0.025	99.82%	0.18%	-0.125	-41.67%
821	19.8	- -	- -			- -	- -	TOO DARK TO RED					
823	- -	- -	- -			- -	- -	TOO DARK TO READ					
825	17.2	2.5	0.175	0.58	47.90%	2:51	88.89%		3.075	121.77%	-21.77%	-0.125	-41.67%
826	15.2	3.25	0.275	1.04	85.18%	2:40	95.00%		1.075	107.61%	-7.61%	-0.025	-8.33%
828	15.2	2.5	0.175	0.66	54.21%	2:45	92.12%		1.075	107.61%	-7.61%	-0.125	-41.67%
830	16.375	3	0.275	0.96	79.07%	2:44	92.68%		2.25	115.93%	-15.93%	-0.025	-8.33%
832	17	2	0.150	0.51	41.54%	3:53	65.24%	ALMOST TOO DARK TO READ	2.875	120.35%	-20.35%	-0.150	-50.00%
834	14.375	3.25	0.275	1.10	90.07%	2:29	102.01%		0.25	101.77%	-1.77%	-0.025	-8.33%
837	16.3	4	0.375	1.32	108.32%	3:06	81.72%		2.175	115.40%	-15.40%	0.075	25.00%
838						- -	- -	UNREADABLE					
839						- -	- -	UNREADABLE					
841	15	4	0.350	1.34	109.86%	2:28	102.70%		0.875	106.19%	-6.19%	0.050	16.67%
842	15.75	3	0.200	0.73	59.79%	2:36	97.44%		1.625	111.50%	-11.50%	-0.100	-33.33%
843						- -	- -	UNREADABLE					
846						- -	- -	UNREADABLE					
849	15.375	5	0.550	2.05	168.43%	2:14	113.43%		1.25	108.85%	-8.85%	0.250	83.33%
850	15.375	4	0.350	1.30	107.18%	2:27	103.40%		1.25	108.85%	-8.85%	0.050	16.67%
851	13.5	3.5	0.300	1.27	104.63%	2:01	125.62%		-0.625	95.58%	4.42%	0.000	0.00%
855	14.1	5.5	0.550	2.24	183.67%	2:24	105.56%		-0.025	99.82%	0.18%	0.250	83.33%
856	13.25	2.5	0.175	0.76	62.18%	2:16	111.76%		-0.875	93.81%	6.19%	-0.125	-41.67%
857	12.3	3	0.200	0.93	76.56%	2:38	96.20%	TOO DARK	-1.825	87.08%	12.92%	-0.100	-33.33%
858	13.875	4.5	0.375	1.55	127.25%	2:40	95.00%		-0.25	98.23%	1.77%	0.075	25.00%
961	11.3					- -	- -	TOO DARK TO READ					
866						- -	- -	UNREADABLE					
863						- -	- -	UNREADABLE					
871	13.4	4.5	0.350	1.50	122.98%	2:40	95.00%		-0.725	94.87%	5.13%	0.050	16.67%
874	12.1	2.5	0.175	0.83	68.10%	- -	- -	TOO DARK TO READ	-2.025	85.66%	14.34%	-0.125	-41.67%
877						- -	- -	UNREADABLE					
878	14.375	5	0.500	1.99	163.77%	2:20	108.57%		0.25	101.77%	-1.77%	0.200	66.67%

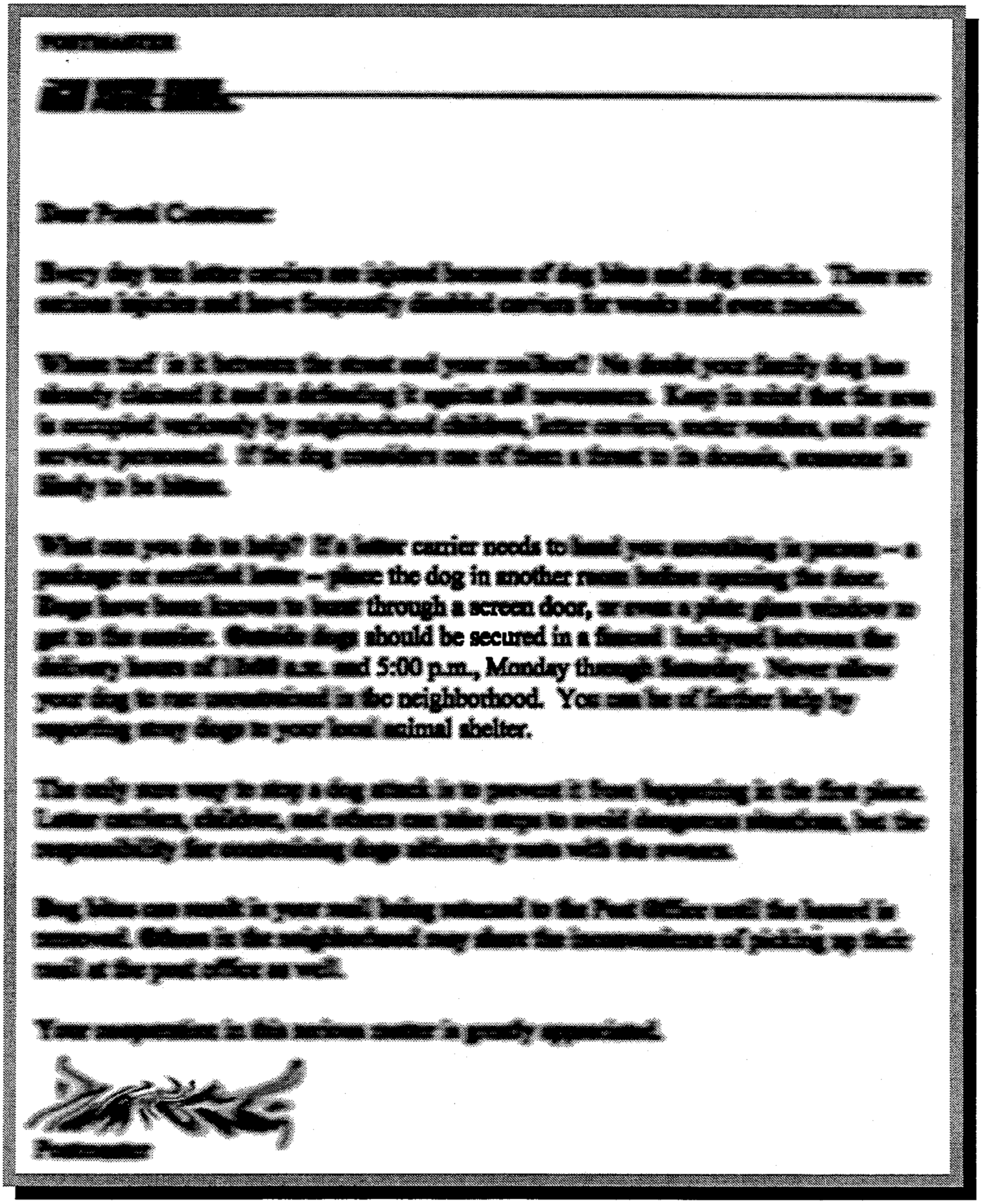


FIGURE 27. Perceived Letter.

POSTMASTER

UNITED STATES
POSTAL SERVICE.

Dear Postal Customer:

Every day ten letter carriers are injured because of dog bites and dog attacks. These are serious injuries and have frequently disabled carriers for weeks and even months.

Whose turf is it between the street and your mailbox? No doubt your family dog has already claimed it and is defending it against all newcomers. Keep in mind that the area is occupied variously by neighborhood children, letter carriers, meter readers, and other service personnel. If the dog considers one of them a threat to its domain, someone is likely to be bitten.

What can you do to help? If a letter carrier needs to hand you something in person – a package or certified letter – place the dog in another room before opening the door. Dogs have been known to burst through a screen door, or even a plate glass window to get to the carrier. Outside dogs should be secured in a fenced backyard between the delivery hours of 10:00 a.m. and 5:00 p.m., Monday through Saturday. Never allow your dog to run unrestrained in the neighborhood. You can be of further help by reporting stray dogs to your local animal shelter.

The only sure way to stop a dog attack is to prevent it from happening in the first place. Letter carriers, children, and others can take steps to avoid dangerous situations, but the responsibility for constraining dogs ultimately rests with the owners.

Dog bites can result in your mail being returned to the Post Office until the hazard is removed. Others in the neighborhood may share the inconvenience of picking up their mail at the post office as well.

Your cooperation in this serious matter is greatly appreciated.

Postmaster

FIGURE 28. Real Letter.

Findings of Quantification Study

This experiment shows that the Irlen effect is real, that the energy spectrum presented to the eye of a dyslexic is capable of altering his visual and cognitive performance to a significant extent (for both better or worse).

By varying the energy spectrum presented to the eye of this dyslexic test subject, we were able to produce a reading speed variation of 80% of normal with reading speed varying from 65% to 145% of normal.

This reading speed variation does not appear to be an independent variable, but ultimately is caused by changes in angle of eye span and focal length, with significant changes in these parameters resulting from the spectral energy shift presented to the eye's vision system. The angle eye span varies from 42% to 242% of normal, and focal length varies over a range of 4.9, inches, which represents a change from 87% to 122.7% of normal over the spectral range used in this test, as shown in Figure 29.

This wide range of change in focal length was a totally unexpected phenomenon, lying outside the bounds of anything predicted by the normal theories of human vision or reported in the scientific literature on the subject, and may represent a unique characteristic of this type of dyslexia.

The various subjective factors (brightness, clarity of letters, sustainability of focus, and perception rating) also showed a general correlation with reading speed, generally getting worse as reading speed deteriorated and better as reading speed improved.

Several of these subjective factors also appear to moderately correlate with each other.

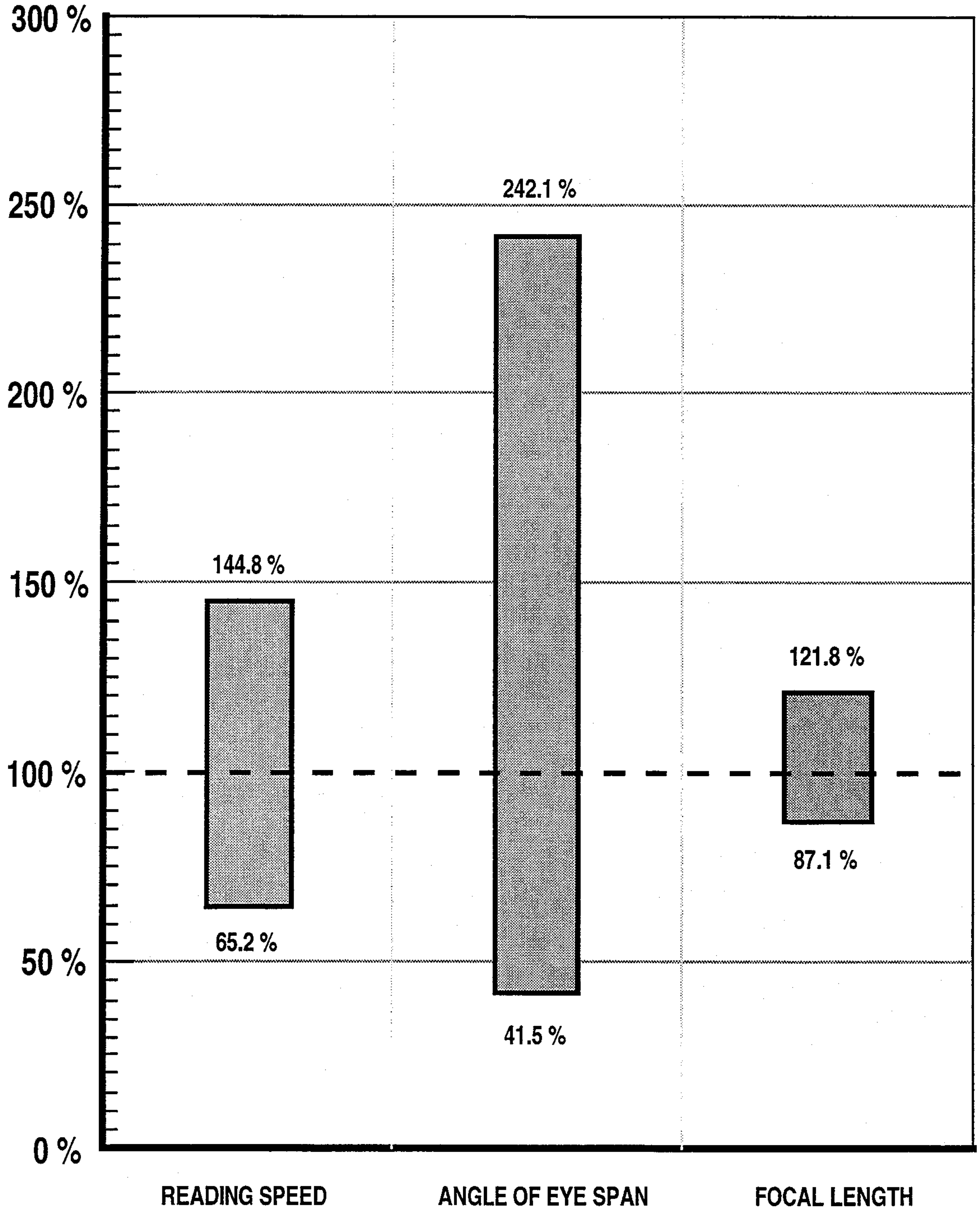


FIGURE 29. Variation of Major Performance Factors.

INVESTIGATION INTO THE REASON FOR THE IRLEN EFFECT

APPROACH

To attempt to develop a better understanding of what is going on and in the hope of a finding a more positive correlation for the phenomenon, the results of this test were subjected to a more sophisticated mathematical and statistical analysis. The approach taken was to reduce the energy spectrum, presented to the test subject's eye by the filters, into components corresponding to the energy absorption responses of the individual cone dyes and then to analyze the resulting data in a series of mathematical models representing various hypotheses for the basis of the Irlen phenomenon or theories of human color vision. The methodology used to break the spectrum into components is discussed in the following paragraphs and is followed in the next section by a discussion of the relevant successful model and its results.

ANALYSIS TECHNIQUE

The human eye has four sets of receptors in it, each of which has a normal frequency response profile. This normal eye frequency response curve pattern has been extensively investigated. This "normal" distribution for frequency responses of eye receptors is today represented by an internationally recognized set of standards produced by the *Commisione International de l'Eclairage.* These standards are know as the C.I.E. 1931 Colorimetric Standard Observer and the C.I.E. 1951 Scotopic Standard Observer. (There are actually two standard Colorimetric Observers, a C.I.E. 1931 and a C.I.E. 1964. For this analysis the C.I.E. 1931 Colorimetric observer was used.) For the purpose of this analyses both the C.I.E. 1931 Colorimetric Observer and the C.I.E. 1951 Scotopic Observer were graphed on one diagram, shown in Figure 30. [4]

[4] This curve is actually represented by a set of tabulated data, which is available in several of the cited references. The values used in this study were taken from Judd, pp. 126-127, and Wyszecki, p. 378.

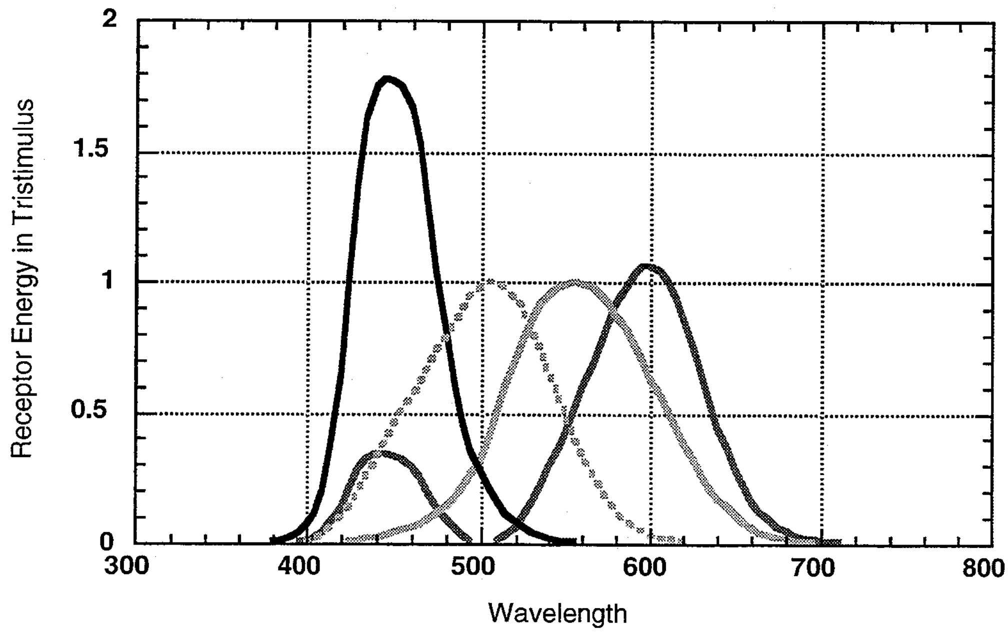
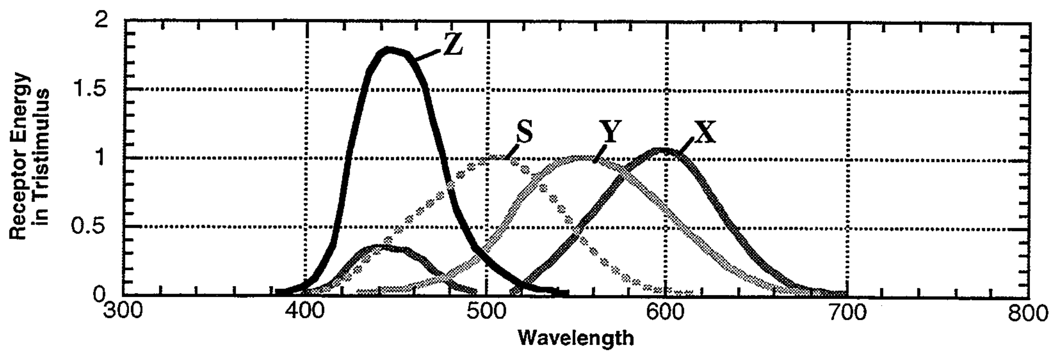
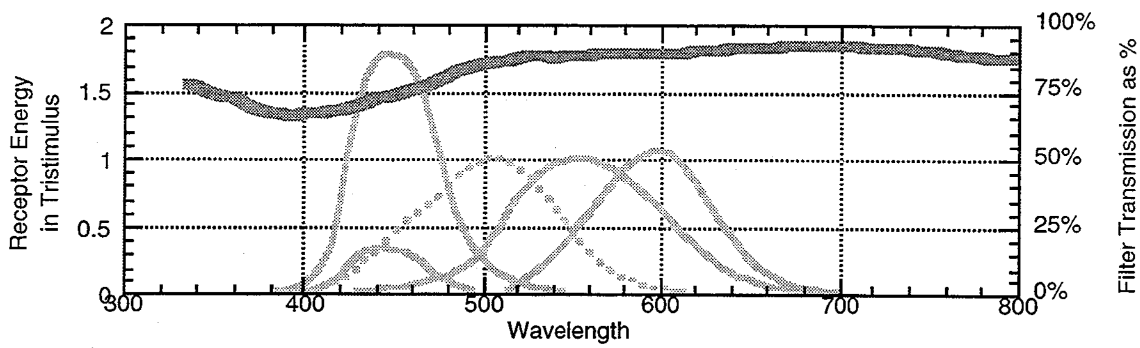


FIGURE 30. C.I.E. 1931 Colorimetric Standard Observer and C.I.E. Scotopic Observer Function Overlay.

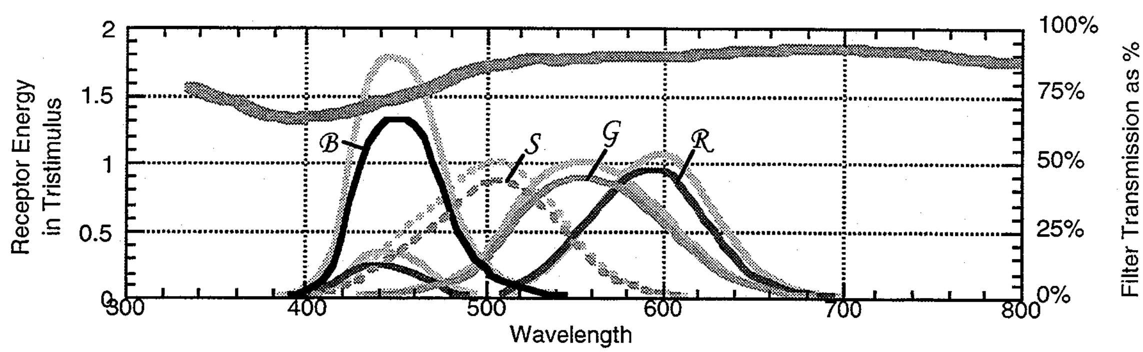
For the purposes of this analysis, this set of standard eye responses was then mathematically modified based on the filter transmission curves given in Appendix A. This produced a transmuted light response curve, which represents the light that the test subject's eye should see, if he were normal (see the discussion of this presumption of normalcy in the Experimental Parameter section). An example of this process is given in Figure 31.



Standard Observer Eye Response Curves



Standard Observer Eye Response Curve Plus Filter Transmission Curve



Resultant Transform Curve Representing the Light Available to the Receptors in the Test Subjects Eye.

FIGURE 31. Transformation Example.

This transformation process was done of each of the 33 filter curves for which reading data were available. The resultant transformation curves were then quantified in mathematical terms, for use in subsequent analyses.

Cone Energy Transformation Curves Definitions

$X(\lambda)$	The frequency response curve for the red cone of the eye (shown for the C.I.E. 1931 standard colorimetric observer in Figure 30)
$Y(\lambda)$	The frequency response curve for the green cone of the eye (shown for the C.I.E. 1931 standard colorimetric observer in Figure 30)
$Z(\lambda)$	The frequency response curve for the blue cone of the eye (shown for the C.I.E. 1931 standard colorimetric observer in Figure 30)
$S(\lambda)$	The frequency response curve of the rod receptors of the eye (shown for the C.I.E. 1931 standard colorimetric observer in Figure 30)
$\int X(\lambda)$	The energy energizing the red cones of the eye as represented by the area under the frequency curve of the red cones (shown for the C.I.E. 1931 standard colorimetric observer in Figure 32)
$\int Y(\lambda)$	The energy energizing the green cones of the eye as represented by the area under the frequency curve of the green cones (shown for the C.I.E. 1931 standard colorimetric observer in Figure 33)
$\int Z(\lambda)$	The energy energizing the blue cones of the eye as represented by the area under the frequency curve of the blue cones (shown for the C.I.E. 1931 standard colorimetric observer in Figure 34.)
$\int S(\lambda)$	The energy energizing the rods of the eye as represented by the area under the frequency curve of the rods (shown for the C.I.E. 1953 standard scotopic observer in Figure 35)

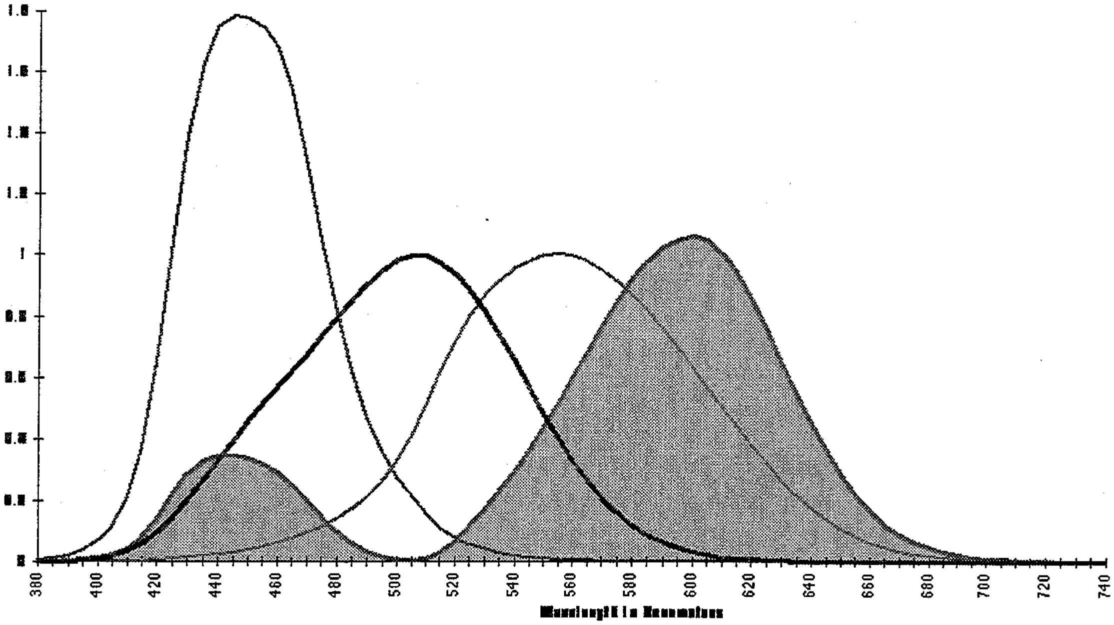


FIGURE 32. Energy Energizing the Red Cones of the Eye.

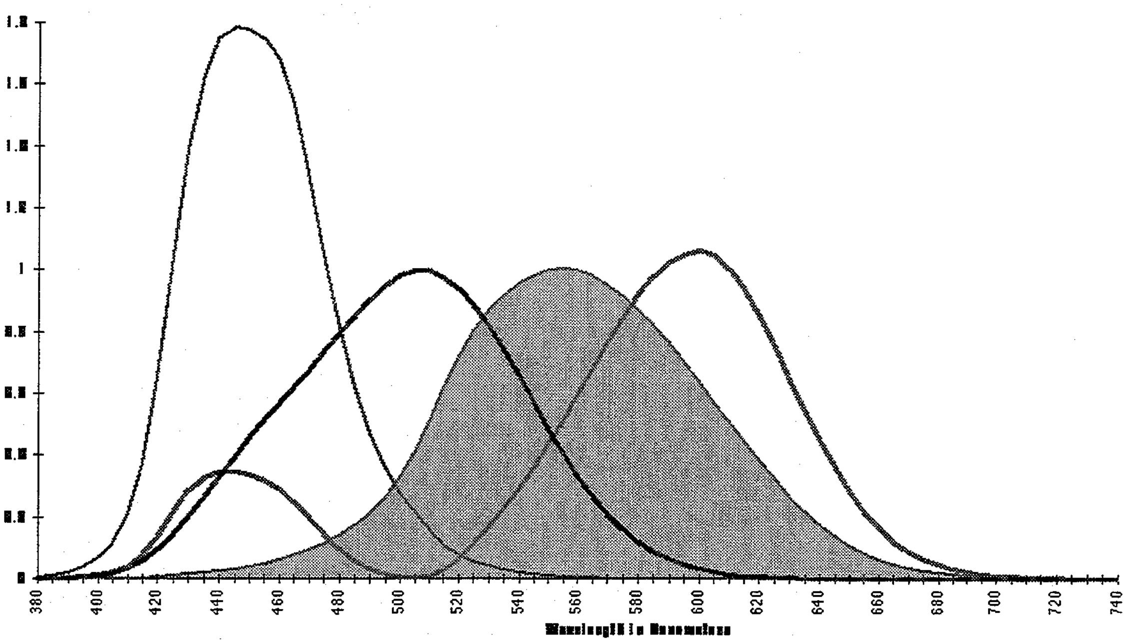


FIGURE 33. Energy Energizing the Green Cones of the Eye.

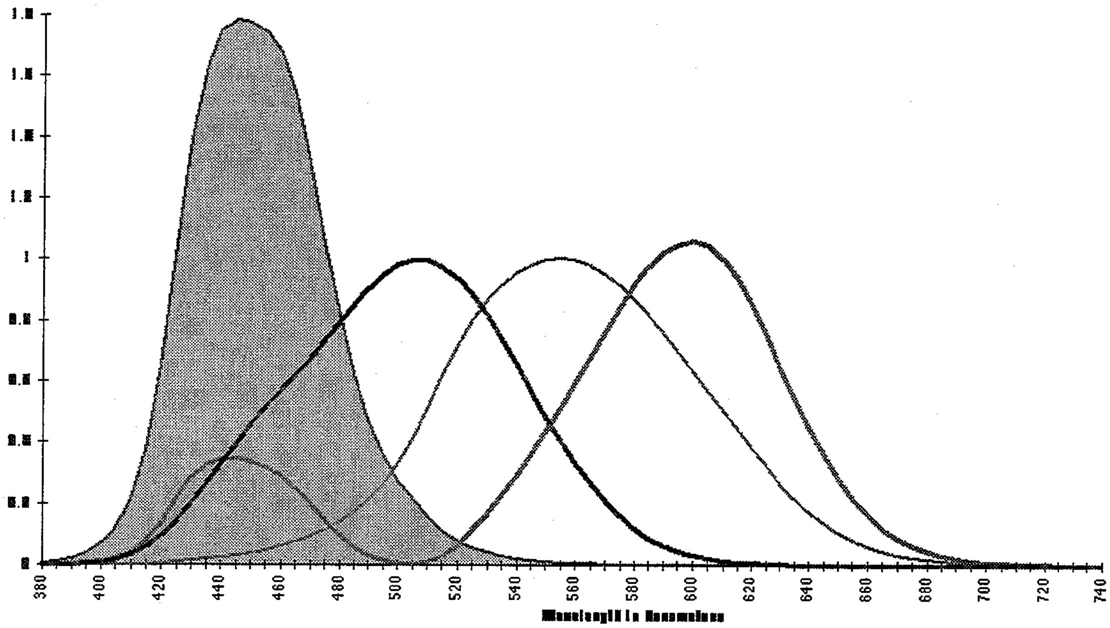


FIGURE 34. Energy Energizing the Blue Cones of the Eye.

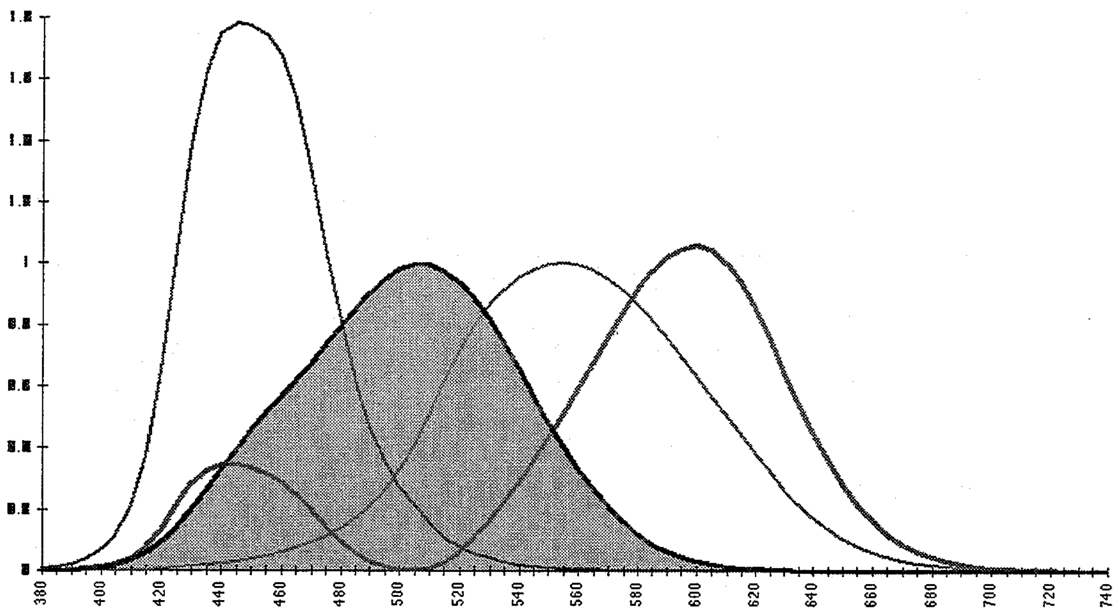


FIGURE 35. Energy Energizing the Rods of the Eye.

Tabulation of Filter Transformations Values

A table of the results of these transformations representing the light energy component available to each of the visual receptors of test subject's eyes was developed from these data and is presented in Table 4. The curve transformations themselves are contained in Appendix B.

TABLE 4. Receptor Energy Transformation Calculation Results Sheet.

Filter No.	Transformation Energy Values			
	$\int X(\lambda)$	$\int Y(\lambda)$	$\int Z(\lambda)$	$\int S(\lambda)$
None	106.85	106.85	106.86	97.07
802	71.36	53.70	39.36	28.84
804	93.02	94.42	79.99	81.00
805	85.18	86.59	49.36	63.45
806	77.69	80.61	9.54	41.90
807	77.20	77.07	5.08	32.64
809	75.70	69.01	2.29	22.97
810	78.30	77.55	17.35	42.16
811	70.75	58.71	22.96	28.71
813	71.23	54.71	4.66	11.55
815	57.19	40.53	0.28	8.26
817	54.15	35.07	1.14	5.53
818	39.91	21.99	2.54	2.55
819	40.57	21.98	3.18	2.18
825	83.41	70.08	75.84	56.69
826	70.24	49.64	50.02	29.19
828	71.05	50.30	47.95	28.27
830	62.28	39.90	46.53	24.15
832	30.80	13.93	14.18	4.28
834	72.39	55.64	62.19	41.70
837	26.52	11.67	19.61	6.17
841	27.62	21.24	67.55	39.88
842	35.43	30.50	74.03	47.99
849	59.38	66.44	93.23	79.63
850	25.49	29.88	82.04	56.23
851	17.03	17.92	64.36	40.51
855	43.46	51.50	85.65	70.73
856	12.77	13.94	62.35	40.69
857	13.06	11.00	63.76	34.11
858	15.97	22.15	66.59	50.60
871	11.64	30.06	10.03	32.16
878	32.23	54.41	10.00	41.13

Discussion of Experimental Parameters

Since this test was originally conceived and run to determine experimental design, several factors were not wholly controlled or were arbitrarily selected that might alter the results slightly but would probably not alter the general nature of the findings. These factors include the following:

1. The use of an incandescent light source, which while generally perceived to be white does not, in reality, have a flat spectral output that covers the whole visual range.

2. The use of the C.I.E. 1931 observer as the standard for analysis. This was done deliberately on the basis of the fact that it was derived on the basis of a 1-, 2-, and 4-degree observer, whereas the more modern C.I.E 1964 observer standard was derived on the basis of a 10-degree observer. [5] Since the subject in this test case came from the Irlen symptomatology subgroup identified as having a limited perception span, it was felt that it would be a better fit to use the C.I.E 1931 narrower-span observer data as the analysis standard. (Indeed, the experimental data bore this out and showed that the subject had a perception span of under 3 degrees.)

3. The presumption of normalcy of the test subject in conforming to the C.I.E. 1931 standard is the greatest imponderable in the experiment and its subsequent analysis. For when the *Commisione Internationale de l'Eclairage* originally derived and defined what is today known as the C.I.E. 1931 standard observer, it derived it as a normalized average of a selected population sample, which excluded from the database for deriving the "standard observer" those subjects (about 20% of the population) that experimentation had showed were not "normal" observers. The C.I.E. standard observer is therefore a biased statistical average of this select "normal" group. [6]

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[5] Judd and Wyszecki, pp. 153-158.

[6] See Le Grand's discussion of the deviation of the C.I.E. Standard (Chapter 8) and its relation to real observers (Chapter 9).

The problem with the use of the "standard observer" profile in the analysis of this experiment is that there is no reason to believe that individuals with Scotopic Sensitivity Syndrome fit the normal modality of the C.I.E. standard. In fact there is every indication that they probably come from the 20% of the population that the C.I.E. excluded from its normal observer pool. Therefore the use of the standard observer profile in analyzing the data is questionable. Its use is justified on the basis that these are the best data available and that there is no readily available way to measure the true color responses of the test subjects. Such responses indeed may be abnormal and that abnormality may, in fact, be part of the problem that leads to the Scotopic Sensitivity Syndrome condition under investigation. (This question of normalcy did in fact come up in the advanced data analysis, and there is a more detailed discussion on the normalcy or non-normalcy of the individual test subject following.)

ANALYSIS OF DATA

ANALYTICAL TECHNIQUES TRIED

To try to find a reason for the observed phenomenon, the data were subjected to various modes of analysis in the hope of finding a methodology that would permit an explanation of the experimental results and permit an analytical correlation of the findings. These techniques included analysis methods based on several hypotheses for the basis of the Irlen phenomenon and theories of human color vision. These included the following:

1. A straight constituency energy balance of the spectrum inputs to the eye receptors versus performance

2. A model based on the Classic Three-Cone Theory of Human Vision

3. A model based on the Hue Theory of Human Color Vision as derived by Hurvich and Jameson in the 1950s [7]

4. A whiteness analysis based on the various "whiteness channel" spectral energy inputs as proposed by various theories and models of human vision

While extensive efforts were put into these approaches, the only finding that can be generated from this work is that one can fill up a 500-megabyte hard drive with graphs and statistical analysis by these methods and have only uncorrelatable garbage to show for one's effort at the end of the study. [8]

RECEPTOR FIELD THEORY ANALYSIS

The experimental data did not yield correlatable results until they were analyzed using the principles of the Receptor Field Theory of Human Vision. Under this methodology the experimental results do correlate and produce a set of interesting and significant findings.

In reality, several methods involving this theory were tried.

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[7] While the Hurvich-Jameson Hue Analysis did not produce a lot of usable data in relationship to the phenomenon under investigation, it did produce an interesting result in relationship to the Hurvich-Jameson Hue Theory and the equation set that goes with it. This is discussed in detail in Appendix C.

[8] As a result it was decided not to include detailed discussion of this vast array of unsuccessful analysis efforts, largely in an attempt to cut down on the already voluminous size of this report.

A Raw Energy Analysis based on this theory was tried and again produced as uncorrelatable garbage. This is attributable to the fact that the total spectral energy variation transmitted though the filter set varies over a range from 100% of normal to 16% of normal input. This variation in absolute total energy level is sufficient to mask the real performance movements caused by the shift of the spectral energy distribution to the eye, if plugged into the equations directly.

A normalized energy analysis was tried next. This means that the highest of the three cone energies was taken to be the 100% level for the eye under that filter and the excitation energy of the other two cones reduced proportionally to it. This system does produce more or less usable results, if one already knows what one is looking for. The method probably has the capability of producing a full range analysis of the phenomenon, with about the same results as those produced by the rationalized analysis method discussed here, although work on this analysis method was stopped before such a conclusion could be fully justified.

The method also has the capability of incorporating an analysis of rod energy levels, something that the rationalized method discussed here does not. This was initially thought to be a useful feature, although no use was found for it in analyzing the test data from this subject.[9] (There are indications that it might be a useful attribute on other individuals based on earlier research by Irlen.) This "normalized method" was abandoned in favor of the rationalized method discussed here and as such is not presented here. (As indicated, its possibility of usefulness was not really determined until the results of the rationalized analysis were well in hand and its previous results re-reviewed.)

The method that was ultimately found to result in correlation of the data was a rationalized receptor field analysis. In this method the spectral energy energizing the color vision system of the eye is reduced to a straight percentage for each cone type with the summation energy levels of the three cones equating to 100% for any given filter. This methodology discounts the possible effect of gross light level on the vision performance of the test subject. It also makes the assumption that the expansion or contraction of the test subject's iris will equalize the light level reaching the retina of the eye to some "nominal normal level."[10]

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[9] This may also be the result of a lack of statistical sophistication in looking for rod intrusion into the color vision function. As a result of the findings of this study, a much more sophisticated method of hunting for rod intrusion was postulated than anything tried (during this phase of analysis) and is addressed in the Discussion on Rod intrusion in Appendix D.

[10] There is some question as to the total validity of this assumption. There is considerable anecdotal evidence that total gross light level and quality of light may affect these types of dyslexic individuals significantly. However, since light level was neither controlled nor measured in this experiment, no other assumption was really possible.

It must also be acknowledged that absolute light level, quality of light, and background lighting varied more than was really desirable. In retrospect this was probably an error in the design of the experiment and which, as discussed elsewhere, probably represents a significant source of error and variation in the experiment.

When the data were analyzed by this rationalized method, the experimental data were found to correlate and make sense. It was found that even the subjective data that were initially taken and believed to be "useless background information" were analyzable by this method, correlate, and make sense to a surprising degree (far beyond any original rational expectation).

RECEPTOR FIELD ANALYSIS OF TEST RESULTS

Background Discussion of Receptor Field Theory of Human Vision

In 1872 Ewald Hering proposed a theory of vision based on a six-factor response on the part the eye: white-black, yellow-blue, and red-green. [11] This theory was based on empirical psychological response observations as opposed to having a physiological base at the time. This theory of vision, which became known as the Hering Opponent-Color Theory, while it appeared to be psychologically valid and useful in that regard, was heavily criticized for many years[12] because it seemed to be at variance with the three-cone physiology construction of the eye. Nevertheless, since it appeared to reflect the psychological reaction of individuals to color better than other theories (and was supported by a significant amount of psychological reaction data), it was retained for that propose.

The Hering Opponent-Color Theory was quantified in 1955 by Leo M. Hurvich and Dorothea Jameson who derived equations for the psychological response of observers to its basic tenets. [13] On the basis of this, Hurvich and Jameson derived a general theory of color vision, which became known as the Hering, Hurvich-Jameson Opponent-Color Theory of Color Vision (more commonly referred to simply as the Hue Theory). This Hurvich-Jameson Theory became one of the standard textbook theories of human color vision for about 40 years and is still widely cited.

[11] Le Grand, pp. 466-468.
[12] Le Grand, pp. 466-449.
[13] Jameson and Hurvich (1955-1956). See also Wyszecki & Stiles, pp. 446-449.

In 1983 E. Zrenner offered a proposed physiological bases for the Hering, Hurvich-Jameson Opponent-Color Theory of Color Vision. Zrenner proposed, based on his work in non-human primate vision, that cones were organized into receptor fields of the general type shown in Figure 36.

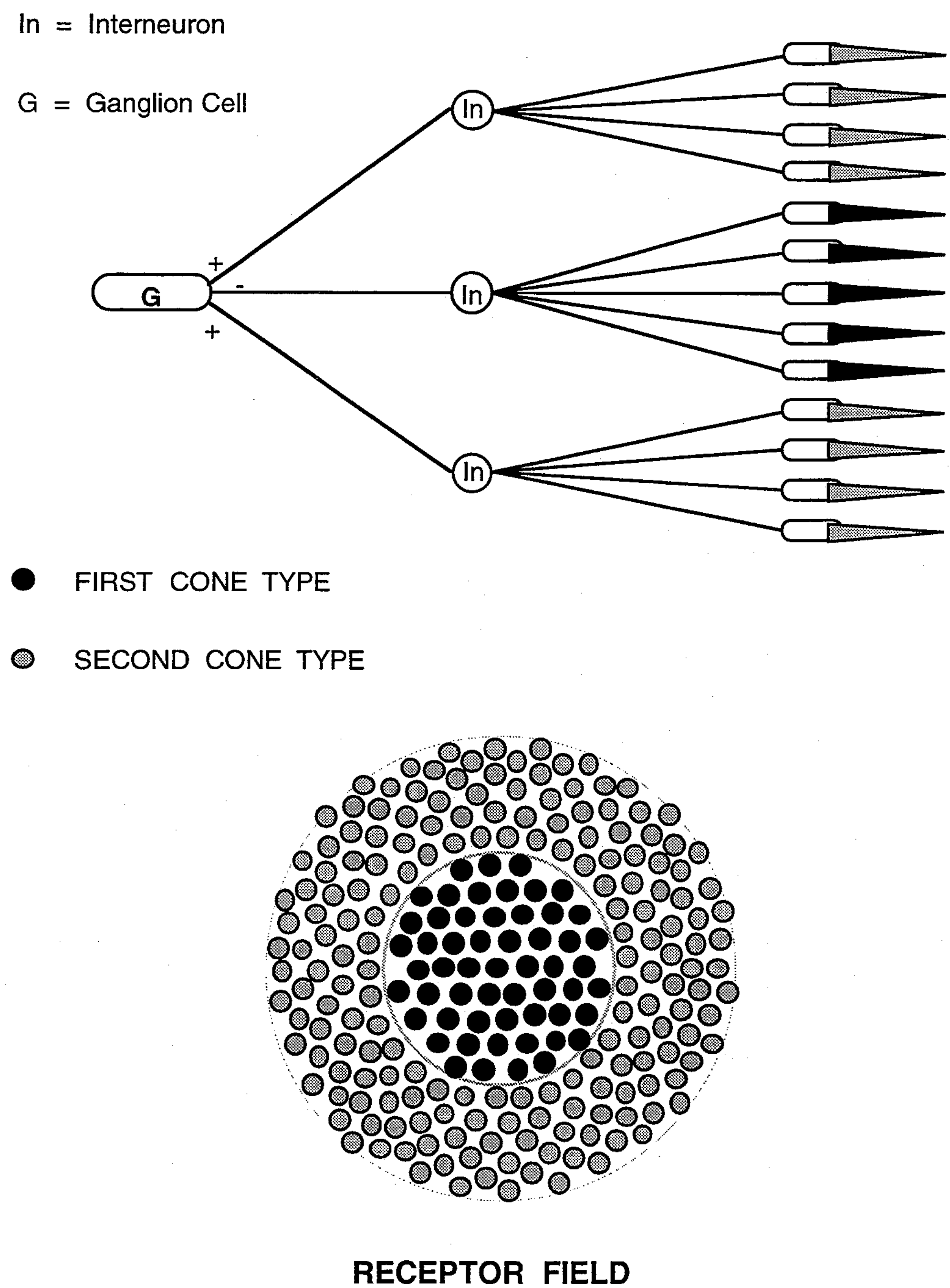

FIGURE 36. Generalized Receptor Field.

These proposed fields were composed of two zones of differing cone composition. Zrenner held that there were eight types of receptor fields organized into two groups:

+R-G, -R+G, +G-R, -G+R

+B-Y, -B+Y, +Y-B, -Y+B

Where

R = The summed energy output of the red cone array collated at the ganglion cell field receptor node of each field, or $R = \sum \int X(\lambda)$ in the nomenclature of this report

G = The summed energy output of the green cone array collated at the ganglion cell field receptor node of each field, or $G = \sum \int Y(\lambda)$ in the nomenclature of this report

B = The summed energy output of the blue cone array collated at the ganglion cell field receptor node of each field, or $B = \sum \int Z(\lambda)$ in the nomenclature of this report

Y = The summed energy output of a zone of a Red and green cone array collated at the ganglion cell field receptor node of each field, or $Y = k_r \sum \int X(\lambda) + k_g \sum \int Y(\lambda)$ in the nomenclature of this report. Where k_r and k_g are constants of proportionality between the of the energy red and green cones, were $k_r + k_g = 1$[14]

Zrenner held that the physiologically and neurological system was capable of determining and using the positive and negative values of the field signal in its processing function.

Zrenner also held that the summed array energy levels of the two zones of the fields were equal, so that the array zones are in direct balance as opposed to proportional balance. A supposition not really supported by scientific evidence but which is accepted here for analytical purpose for lack of better data.

[14] This is usually construed as $k_r = k_g = 0.5$. As part of the non-reported "Normalized Receptor Field Energy Analysis" of this study, a rather extensive iterative test of this hypothesis was conducted. The results of this exercise show that proportionally verifying k_r and k_g do not affect the out come of this set of test results in a meaningful manner and that therefore the $k_r = k_g = 0.5$ assumption is probably correct within the limits of error of this experiment.

It was Zrenner's position that this balance function controlled and/or modified the timing function of the color vision signal to the brain. [15]

Under the Zrenner theory the Yellow of the Hering, Hurvich-Jameson Opponent-Color Theory, is produced by fields composed of a zone of blue cones and a yellow field zone composed of red and green cones. As depicted in Figure 37. (This does account for the observed psychological phenomenon involved in the Opponent-Color Theory.)

Zrenner held that the red and green cones could occupy either the inner or outer field zones as depicted in Figures 38 and 39 and that blue cones occurred only in the center of the blue-yellow field as shown in Figure 37, with the neurological net supporting the field accounting for the positive/negative signal function characterization. [16]

A modification to the Zrenner theory has been proposed based on the work of De Monasterio, Gouras, and Tolhurst, which involved research into the color vision structure of Rhesus monkeys, which indicates three types of yellow receptor fields: [17]

B-R

B-G

B-Y (Where Y is the weighted sum of R & G)[18]

These fields are depicted schematically in Figure 40.

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[15] Zrenner, 1983. Cited from: Widdel and Post, p. 107.

[16] Exactly how and why Zrenner holds that there are four types of B-Y receptor fields, as opposed to two, if this hypothesis is true, is not really discussed in the source literature. In this regard, the Zrenner theory and its supporting equations set do not appear to be in harmony with each other. Zrenner's theory is here cited on the basis of published literature, the discontinuity is noted, and accepted on the assumption that Zrenner has a valid "deep" physiological reason for his holding, not stated in the used source literature. (The noted theoretical discontinuity is in any case irrelevant to our analysis here, attributable to other limitations, as will be seen shortly.)

[17] De Monasterio, 1975 and 1980; cited from Widdel, pp. 104-108.

[18] Essentially a modification of Zrenner field construction made to account for the minor difference in energy output between red and green cones.

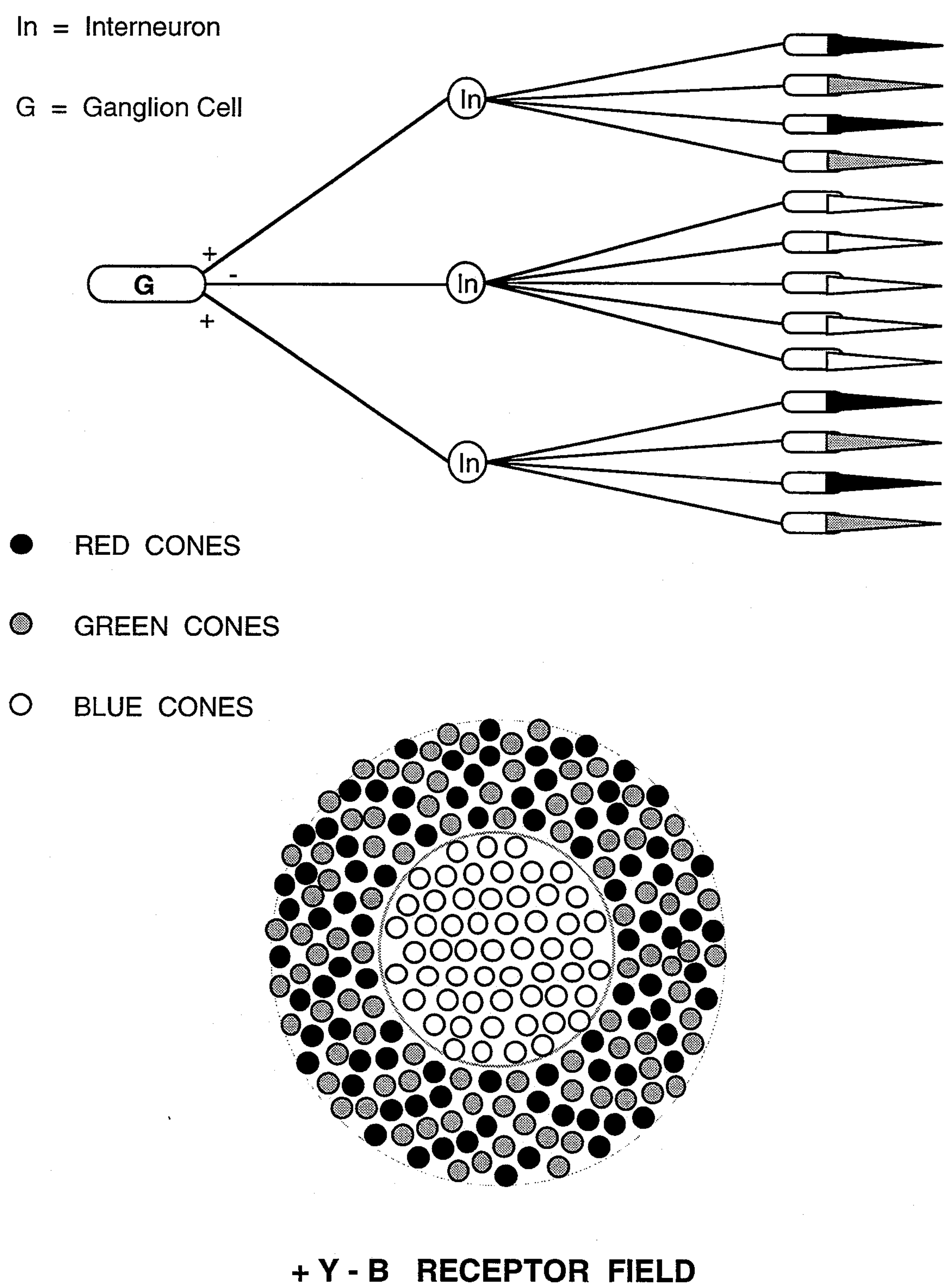

FIGURE 37. +Y-B Receptor Field.

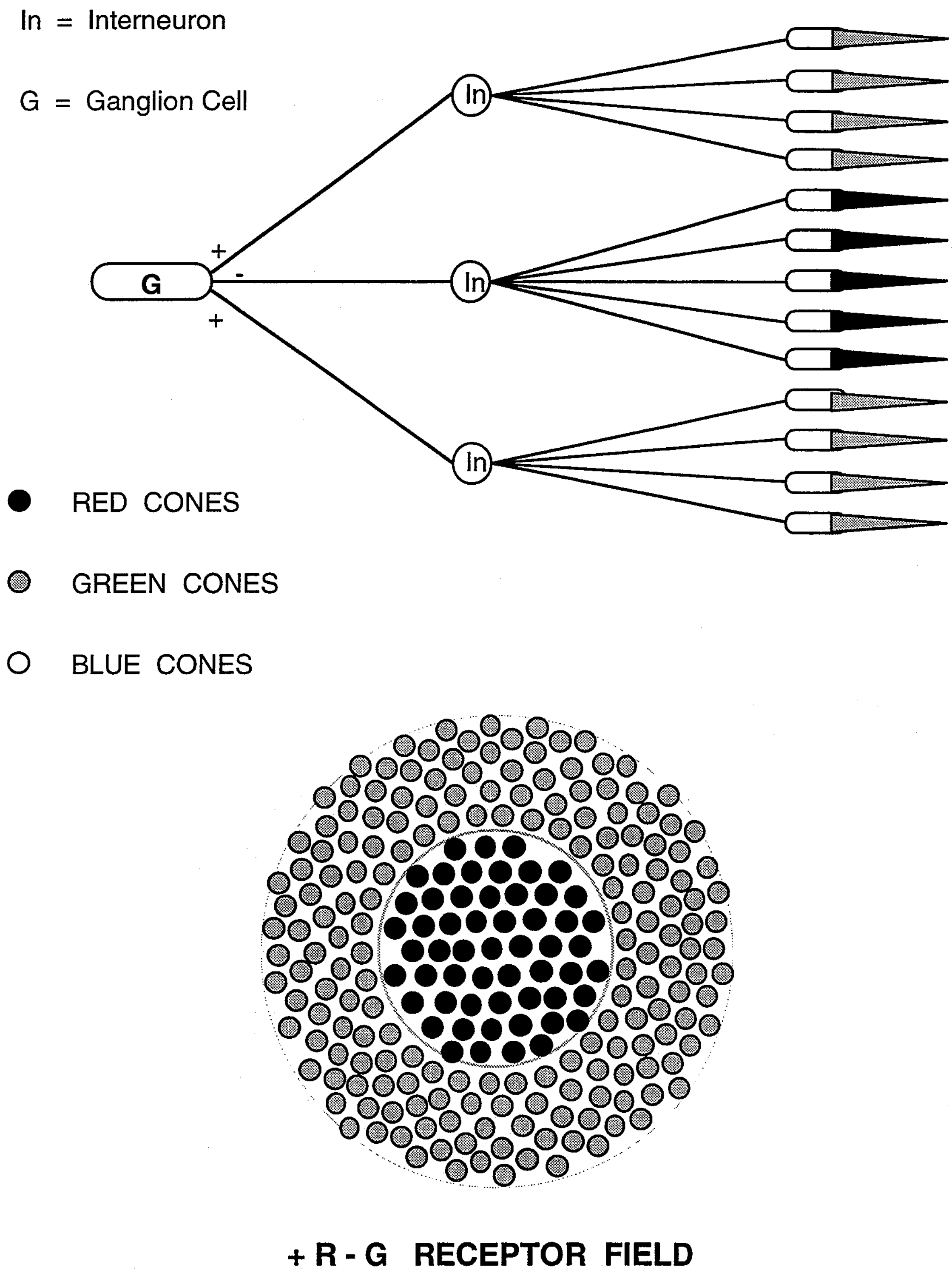

FIGURE 38. +R-G Receptor Field.

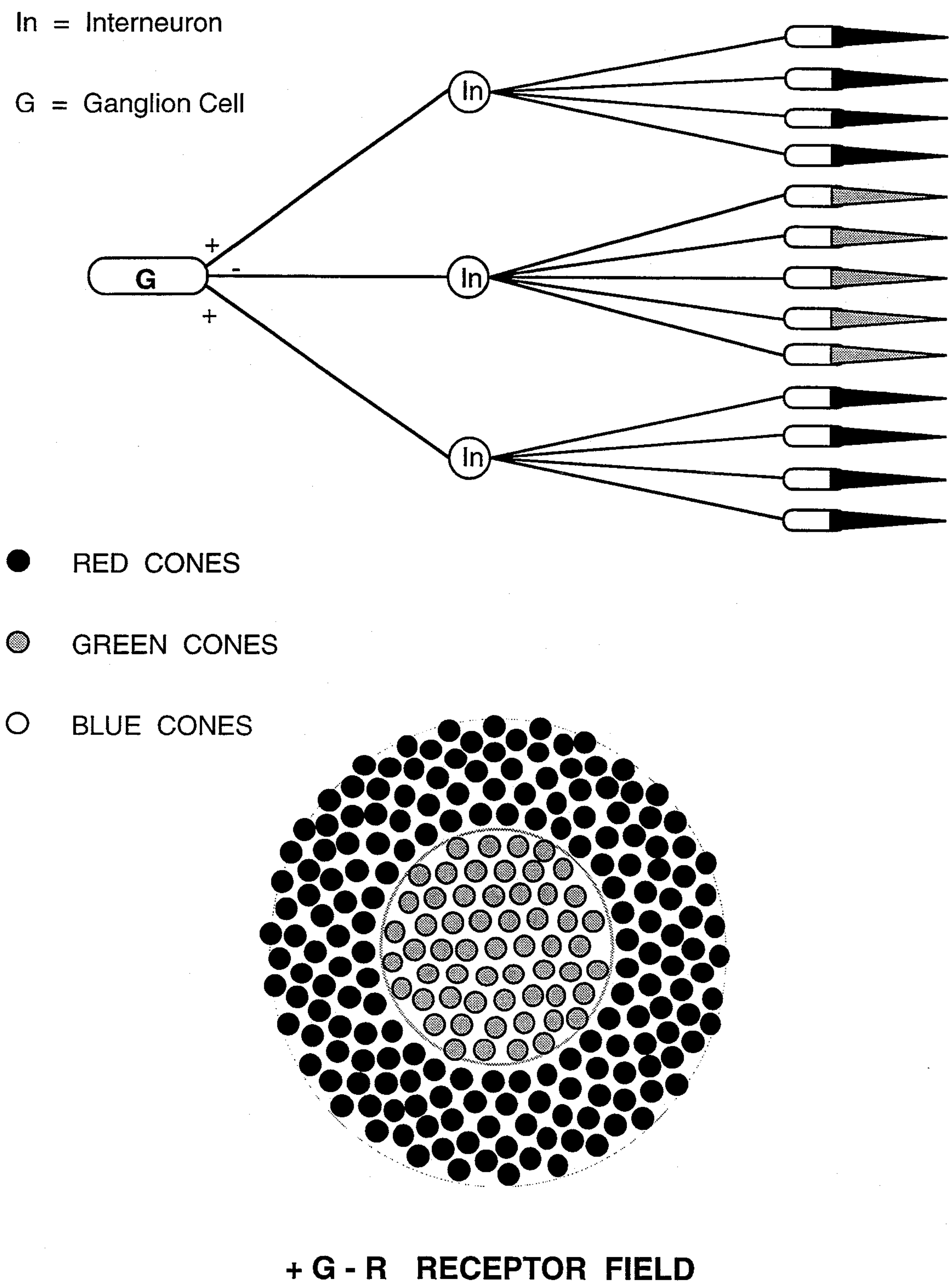

FIGURE 39. +G-R Receptor Field.

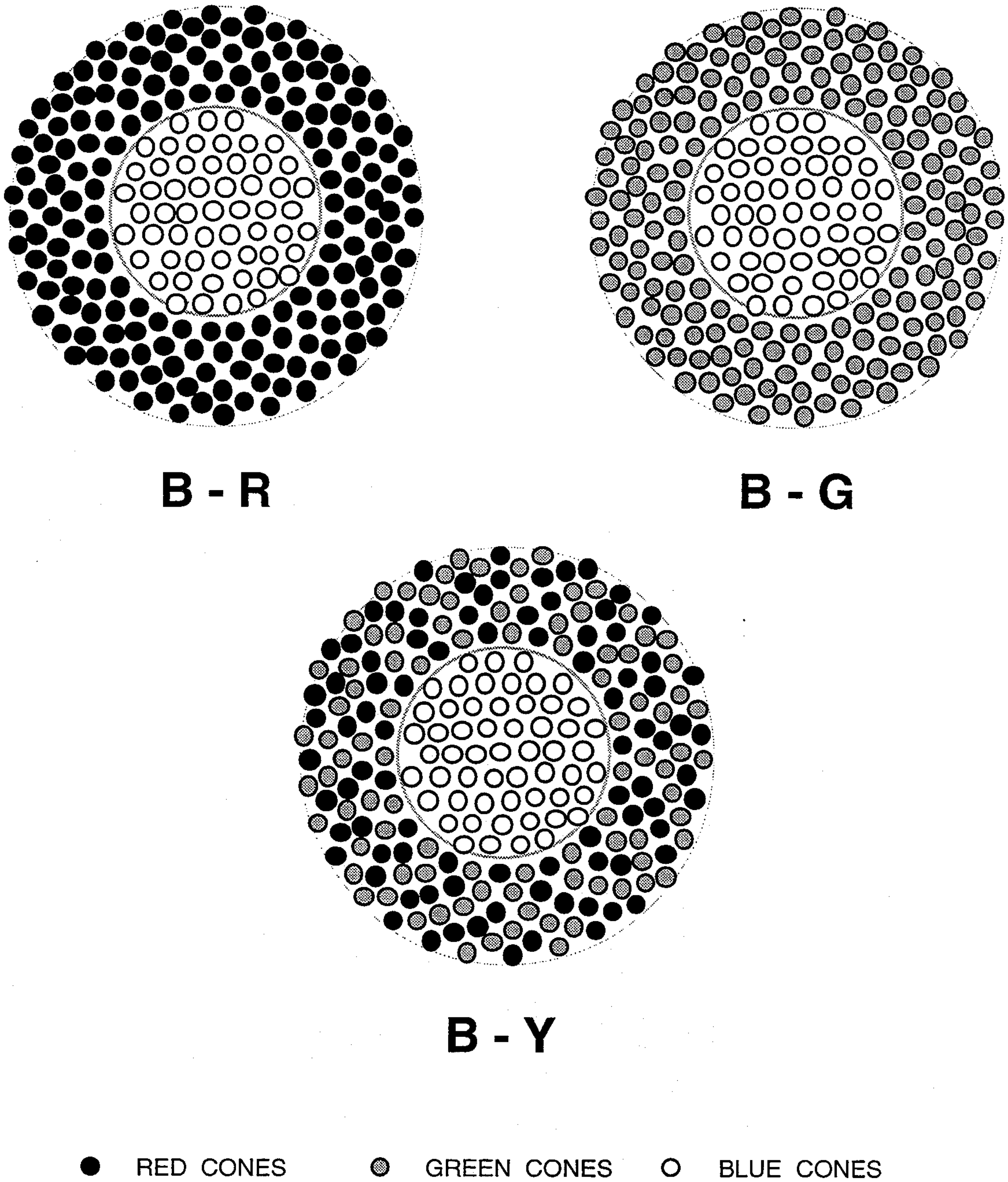

FIGURE 40. Hypothesized De Monasterio "Y" Receptor Fields.

Since The Zrenner-De Monasterio Receptor Field Theory offers a timing variance explanation for color vision response and many proponents of deep-brain processing problems as the basis for dyslexia held that it is a deep-brain timing problem, it was thought worth while to run an analysis to see if a correlation existed between reading performance and eye response and any of the proposed receptor field compositions that would account for Scotopic Sensitivity Syndrome and/or its modification by light spectral composition.

Analysis Technique

To determine if there was a relationship between receptor field composition and visual performance, a set of these hypothesized receptor fields was analyzed against the test subject's performance. This required some simplifying assumptions, namely, that the rule of proportionality holds for all the fields and that $R = \sum \int X_\lambda \approx \int X_\lambda$ for calculation purpose and that k_r and k_g are ≈ to 0.5.[19] Based on this, the energy product of each type of hypothesized receptor field was analyzed against the quantifiable and subjective factors measured in this test. The hypothesized field sets chosen for this analysis included the following field sets:

+R-G, -R+G, +G-R, -G+R

+B-Y, -B+Y, +Y-B, -Y+B

[19] This is based on two generally accepted suppositions, namely, that the energy levels produced by each type of cone are substantially equal or at least within 4% or 5% of each other, and that the numbers of green, red, and blue cones in the system are essentially equal.

No real reason exists to believe that either of these generally accepted suppositions are in fact actually true at a physiological level. The equal energy supposition is actually based on psychological observations that are at least 4th or 5th derivatives of the physiological reality that it purports to represent and may not actually reflect the real workings of the eye. The second supposition has even less basis in fact, for there is some physiological evidence that the number of blue cones is significantly fewer than that of red and green cones and that the eye's receptors processing neural net actually does work by proportional processing and adjusts the signal for this fact. These facts, not withstanding the generally accepted suppositions, were used for calculation purposes here, in the hope that if a real correlation between the factors existed it would exhibit itself, a possibility for which there are psychological data to justify. (This is coupled with the fact that current state of the art, as revealed by the literature, does not offer us a lot of other options.)

as translated into

+B-(0.5R+0.5G), -B+(0.5R+0.5G),

+(0.5R+0.5G)-B, -(0.5R+0.5G)+B,

+B-G, -B+G, +G-B, -G+B

+B-R, -B+R, +R-B, -R+B

As a result of the limitation of the mathematical model, only the absolute value of a field set can be derived and used for analytical purposes, with the math model being unable to account for a mere sign change or sign location change in a receptor field in the analysis framework, the result of any such change merely being a change in the sign of the absolute value of receptor field's strength. As a result only the four "class types" of receptor fields can be analyzed for their effect on performance. [20]

Data-Formatting for Rationalized Analysis

To use the rationalized analysis method, one must first "rationalize" the data by reducing the spectral excitation energies to a percentage basis and then calculate a "Υ" value, which results in the values shown in Table 5 .

These rationalized excitation energy values are then used to calculate the excitation energy levels of the each type receptor field for each filter, as shown in the last four columns of the reformatted experimental results table (Table 6).

[20] This simplification should not be taken as a challenge to the assumption that the physiology of the human vision system can make use of such sign changes or sign location changes in processing. In fact, parts of this analysis indicate that this is in fact probably the case.

TABLE 5. Rationalized Receptor Energy Calculation Sheet.

Filter No.	Transformation Energy Values				Total Energy	Rationalized Energy Values				Y Component Calculation
	$\int X(\lambda)$	$\int Y(\lambda)$	$\int Z(\lambda)$	$\int S(\lambda)$	X+Y+Z	$\mathcal{R}$	$\mathcal{G}$	$\mathcal{B}$	$\mathcal{R}+\mathcal{G}+\mathcal{B}$	
NONE	106.85	106.85	106.86	97.07	320.56	33.33%	33.33%	33.33%	100.00%	33.33%
802	71.36	53.70	39.36	28.84	164.42	43.40%	32.66%	23.94%	100.00%	38.03%
804	93.02	94.42	79.99	81.00	267.42	34.78%	35.31%	29.91%	100.00%	35.04%
805	85.18	86.59	49.36	63.45	221.13	38.52%	39.16%	22.32%	100.00%	38.84%
806	77.69	80.61	9.54	41.90	167.84	46.29%	48.03%	5.68%	100.00%	47.16%
807	77.20	77.07	5.08	32.64	159.35	48.45%	48.36%	3.19%	100.00%	48.41%
809	75.70	69.01	2.29	22.97	147.00	51.50%	46.94%	1.56%	100.00%	49.22%
810	78.30	77.55	17.35	42.16	173.20	45.21%	44.77%	10.02%	100.00%	44.99%
811	70.75	58.71	22.96	28.71	152.42	46.42%	38.52%	15.06%	100.00%	42.47%
813	71.23	54.71	4.66	11.55	130.61	54.54%	41.89%	3.57%	100.00%	48.21%
815	57.19	40.53	0.28	8.26	97.99	58.36%	41.35%	0.28%	100.00%	49.86%
817	54.15	35.07	1.14	5.53	90.36	59.93%	38.81%	1.26%	100.00%	49.37%
818	39.91	21.99	2.54	2.55	64.44	61.93%	34.13%	3.95%	100.00%	48.03%
819	40.57	21.98	3.18	2.18	65.73	61.72%	33.44%	4.83%	100.00%	47.58%
825	83.41	70.08	75.84	56.69	229.32	36.37%	30.56%	33.07%	100.00%	33.47%
826	70.24	49.64	50.02	29.19	169.90	41.34%	29.22%	29.44%	100.00%	35.28%
828	71.05	50.30	47.95	28.27	169.30	41.97%	29.71%	28.32%	100.00%	35.84%
830	62.28	39.90	46.53	24.15	148.71	41.88%	26.83%	31.29%	100.00%	34.36%
832	30.80	13.93	14.18	4.28	58.91	52.28%	23.64%	24.08%	100.00%	37.96%
834	72.39	55.64	62.19	41.70	190.23	38.06%	29.25%	32.69%	100.00%	33.65%
837	26.52	11.67	19.61	6.17	57.80	45.88%	20.19%	33.93%	100.00%	33.04%
841	27.62	21.24	67.55	39.88	116.41	23.73%	18.25%	58.02%	100.00%	20.99%
842	35.43	30.50	74.03	47.99	139.96	25.32%	21.79%	52.89%	100.00%	23.56%
849	59.38	66.44	93.23	79.63	219.06	27.11%	30.33%	42.56%	100.00%	28.72%
850	25.49	29.88	82.04	56.23	137.41	18.55%	21.74%	59.71%	100.00%	20.15%
851	17.03	17.92	64.36	40.51	99.32	17.15%	18.05%	64.81%	100.00%	17.60%
855	43.46	51.50	85.65	70.73	180.61	24.06%	28.52%	47.42%	100.00%	26.29%
856	12.77	13.94	62.35	40.69	89.06	14.34%	15.66%	70.01%	100.00%	15.00%
857	13.06	11.00	63.76	34.11	87.82	14.87%	12.52%	72.61%	100.00%	13.70%
858	15.97	22.15	66.59	50.60	104.70	15.25%	21.15%	63.60%	100.00%	18.20%
871	11.64	30.06	10.03	32.16	51.73	22.49%	58.11%	19.40%	100.00%	40.30%
878	32.23	54.41	10.00	41.13	96.64	33.35%	56.30%	10.35%	100.00%	44.82%

TABLE 6. Reformatted Experimental Results Table With Rationalized Receptor Field Data.

	SUBJECTIVE FACTORS					QUANTITATIVE FACTOR				CALCULATED FACTORS				
Filter No.	Brightness	Clarity of Letters	Flicker Rating	Sustainability of Focus Rating	Perception Rating	Focal Length	Eye Span in Letters	Eye Span in Tape Distance	Angle of Eye Span	Angle of Eye Span Increase as % of Normal	Reading Speed	Reading Speed as % of Normal	Focal Length Change From Normal (in inches)	Focal Length Change From Normal (in %)
NONE	0	0	0	0	0	14.125	3	0.300	1.22	100.00%	2:32	100.00%	0	100.00%
802	+1	+2	+2	+2	+1	14.7	6	0.625	2.44	200.20%	1:53	134.51%	0.575	104.07%
804	+2	+2	+1	+1	+2	14.1	8	0.725	2.95	242.12%	1:45	144.76%	-0.025	99.82%
805	+3	+3	+2	+2	+2	15.2	8	0.750	2.83	232.34%	2:10	116.92%	1.075	107.61%
806	+2	-1	0	+1	-1	14.2	3	0.325	1.31	107.76%	2:46	91.57%	0.075	100.53%
807	-1	+1	+2	0	0	12.7	2.5	0.250	1.13	92.68%	2:42	93.83%	-1.425	89.91%
809	+1	+1	+1	+1	0	14	3.5	0.300	1.23	100.89%	2:58	85.39%	-0.125	99.12%
810	+1	0	+1	+1	0	13.4	2.5	0.250	1.07	87.84%	2:42	93.83%	-0.725	94.87%
811	+1	+2	+1	+2	+2	14.6	4.5	0.450	1.77	145.12%	2:19	109.35%	0.475	103.36%
813	0	+1	+1	0	0	15	5	0.500	1.91	156.95%	2:47	91.02%	0.875	106.19%
815	+2	+2	+1	+1	+2	14.2	3.5	0.250	1.01	82.89%	2:28	102.70%	0.075	100.53%
817	+1	-1	+1	-1	0	13.75	3	0.250	1.04	85.61%	2:28	102.70%	-0.375	97.35%
818	0	+1	+1	-2	-1	13.2	2.5	0.200	0.87	71.34%	2:40	95.00%	-0.925	93.45%
819	-1	+1	+1	-2	-2	14.1	2	0.175	0.71	58.44%	2:45	92.12%	-0.025	99.82%
825	-1	0	+1	-2	+1	17.2	2.5	0.175	0.58	47.90%	2:51	88.89%	3.075	121.77%
826	+1	+1	+2	0	0	15.2	3.25	0.275	1.04	85.18%	2:40	95.00%	1.075	107.61%
828	+1	-1	+1	-2	0	15.2	2.5	0.175	0.66	54.21%	2:45	92.12%	1.075	107.61%
830	-1	+1	0	-1	-1	16.375	3	0.275	0.96	79.07%	2:44	92.68%	2.25	115.93%
832	-2	-2	0	-2	-2	17	2	0.150	0.51	41.54%	3:53	65.24%	2.875	120.35%
834	+1	+1	0	-1	-1	14.375	3.25	0.275	1.10	90.07%	2:29	102.01%	0.25	101.77%
837	-2	-2	0	-2	-2	16.3	4	0.375	1.32	108.32%	3:06	81.72%	2.175	115.40%
841	-2	-1	0	-2	-2	15	4	0.350	1.34	109.86%	2:28	102.70%	0.875	106.19%
842	-2	-1	+1	-2	-2	15.75	3	0.200	0.73	59.79%	2:36	97.44%	1.625	111.50%
849	+2	+2	+2	+2	+2	15.375	5	0.550	2.05	168.43%	2:14	113.43%	1.25	108.85%
850	-1	-1	+1	-1	-1	15.375	4	0.350	1.30	107.18%	2:27	103.40%	1.25	108.85%
851	-1	-2	+1	-1	-1	13.5	3.5	0.300	1.27	104.63%	2:01	125.62%	-0.625	95.58%
855	-1	-1	+2	-1	+1	14.1	5.5	0.550	2.24	183.67%	2:24	105.56%	-0.025	99.82%
856	-2	-2	+1	-1	-1	13.25	2.5	0.175	0.76	62.18%	2:16	111.76%	-0.875	93.81%
857	-3	-2	+1	-1	-2	12.3	3	0.200	0.93	76.56%	2:38	96.20%	-1.825	87.08%
858	-1	+1	+1	+1	+1	13.875	4.5	0.375	1.55	127.25%	2:40	95.00%	-0.25	98.23%
871	-1	+1	+1	+1	+1	13.4	4.5	0.350	1.50	122.98%	2:40	95.00%	-0.725	94.87%
878	+3	+2	+1	+2	+2	14.375	5	0.500	1.99	163.77%	2:20	108.57%	0.25	101.77%

TABLE 6. Reformatted Experimental Results Table With Rationalized Receptor Field Data.

			TRANSFORMATION ENERGY VALUES				ENERGY AVAILABLE		DOMINANT GROUP	RATIONALIZED ENERGY VALUES			
Variance of Focal Length (in %)	Eye Span Tape Distance Variation	Eye Span Tape Distance Variation as %	$\int X(\lambda)$	$\int Y(\lambda)$	$\int Z(\lambda)$	$\int S(\lambda)$	X+Y+Z	% of Total of Normal Light Available	X N Y	$\mathcal{R}$	$\mathcal{G}$	$\mathcal{B}$	$\mathcal{Y}$
0.00%	0.000	0.00%	106.85	106.85	106.86	97.07	320.56	100.00%	N	33.33%	33.33%	33.33%	33.33%
-4.07%	0.325	108.33%	71.36	53.70	39.36	28.84	164.42	51.29%	X	43.40%	32.66%	23.94%	38.03%
0.18%	0.425	141.67%	93.02	94.42	79.99	81.00	267.42	83.42%	X	34.78%	35.31%	29.91%	35.04%
-7.61%	0.450	150.00%	85.18	86.59	49.36	63.45	221.13	68.98%	X	38.52%	39.16%	22.32%	38.84%
-0.53%	0.025	8.33%	77.69	80.61	9.54	41.90	167.84	52.36%	X	46.29%	48.03%	5.68%	47.16%
10.09%	-0.050	-16.67%	77.20	77.07	5.08	32.64	159.35	49.71%	X	48.45%	48.36%	3.19%	48.41%
0.88%	0.000	0.00%	75.70	69.01	2.29	22.97	147.00	45.86%	X	51.50%	46.94%	1.56%	49.22%
5.13%	-0.050	-16.67%	78.30	77.55	17.35	42.16	173.20	54.03%	X	45.21%	44.77%	10.02%	44.99%
-3.36%	0.150	50.00%	70.75	58.71	22.96	28.71	152.42	47.55%	X	46.42%	38.52%	15.06%	42.47%
-6.19%	0.200	66.67%	71.23	54.71	4.66	11.55	130.61	40.74%	X	54.54%	41.89%	3.57%	48.21%
-0.53%	-0.050	-16.67%	57.19	40.53	0.28	8.26	97.99	30.57%	X	58.36%	41.35%	0.28%	49.86%
2.65%	-0.050	-16.67%	54.15	35.07	1.14	5.53	90.36	28.19%	X	59.93%	38.81%	1.26%	49.37%
6.55%	-0.100	-33.33%	39.91	21.99	2.54	2.55	64.44	20.10%	X	61.93%	34.13%	3.95%	48.03%
0.18%	-0.125	-41.67%	40.57	21.98	3.18	2.18	65.73	20.51%	X	61.72%	33.44%	4.83%	47.58%
-21.77%	-0.125	-41.67%	83.41	70.08	75.84	56.69	229.32	71.54%	N	36.37%	30.56%	33.07%	33.47%
-7.61%	-0.025	-8.33%	70.24	49.64	50.02	29.19	169.90	53.00%	N	41.34%	29.22%	29.44%	35.28%
-7.61%	-0.125	-41.67%	71.05	50.30	47.95	28.27	169.30	52.81%	N	41.97%	29.71%	28.32%	35.84%
-15.93%	-0.025	-8.33%	62.28	39.90	46.53	24.15	148.71	46.39%	N	41.88%	26.83%	31.29%	34.36%
-20.35%	-0.150	-50.00%	30.80	13.93	14.18	4.28	58.91	18.38%	N	52.28%	23.64%	24.08%	37.96%
-1.77%	-0.025	-8.33%	72.39	55.64	62.19	41.70	190.23	59.34%	N	38.06%	29.25%	32.69%	33.65%
-15.40%	0.075	25.00%	26.52	11.67	19.61	6.17	57.80	18.03%	N	45.88%	20.19%	33.93%	33.04%
-6.19%	0.050	16.67%	27.62	21.24	67.55	39.88	116.41	36.32%	Z	23.73%	18.25%	58.02%	20.99%
-11.50%	-0.100	-33.33%	35.43	30.50	74.03	47.99	139.96	43.66%	Z	25.32%	21.79%	52.89%	23.56%
-8.85%	0.250	83.33%	59.38	66.44	93.23	79.63	219.06	68.34%	Z	27.11%	30.33%	42.56%	28.72%
-8.85%	0.050	16.67%	25.49	29.88	82.04	56.23	137.41	42.87%	Z	18.55%	21.74%	59.71%	20.15%
4.42%	0.000	0.00%	17.03	17.92	64.36	40.51	99.32	30.98%	Z	17.15%	18.05%	64.81%	17.60%
0.18%	0.250	83.33%	43.46	51.50	85.65	70.73	180.61	56.34%	Z	24.06%	28.52%	47.42%	26.29%
6.19%	-0.125	-41.67%	12.77	13.94	62.35	40.69	89.06	27.78%	Z	14.34%	15.66%	70.01%	15.00%
12.92%	-0.100	-33.33%	13.06	11.00	63.76	34.11	87.82	27.39%	Z	14.87%	12.52%	72.61%	13.70%
1.77%	0.075	25.00%	15.97	22.15	66.59	50.60	104.70	32.66%	Z	15.25%	21.15%	63.60%	18.20%
5.13%	0.050	16.67%	11.64	30.06	10.03	32.16	51.73	16.14%	X	22.49%	58.11%	19.40%	40.30%
-1.77%	0.200	66.67%	32.23	54.41	10.00	41.13	96.64	30.15%	X	33.35%	56.30%	10.35%	44.82%

TABLE 6. Reformatted Experimental Results Table With Rationalized Receptor Field Data.

RATIONALIZED RECEPTOR FIELD ENERGY LEVELS			
R-G	*B-G*	*B-R*	*B-Y*
0.00%	0.00%	0.00%	0.00%
10.74%	-8.72%	-19.46%	-14.09%
-0.52%	-5.40%	-4.87%	-5.13%
-0.64%	-16.84%	-16.20%	-16.52%
-1.74%	-42.34%	-40.60%	-41.47%
0.09%	-45.17%	-45.26%	-45.22%
4.55%	-45.39%	-49.94%	-47.67%
0.43%	-34.76%	-35.19%	-34.97%
7.90%	-23.45%	-31.36%	-27.40%
12.65%	-38.32%	-50.97%	-44.64%
17.01%	-41.07%	-58.08%	-49.58%
21.12%	-37.55%	-58.67%	-48.11%
27.80%	-30.18%	-57.98%	-44.08%
28.28%	-28.61%	-56.89%	-42.75%
5.81%	2.51%	-3.30%	-0.40%
12.13%	0.22%	-11.90%	-5.84%
12.26%	-1.39%	-13.65%	-7.52%
15.05%	4.45%	-10.59%	-3.07%
28.64%	0.43%	-28.20%	-13.88%
8.81%	3.44%	-5.36%	-0.96%
25.69%	13.73%	-11.95%	0.89%
5.48%	39.78%	34.30%	37.04%
3.52%	31.10%	27.57%	29.33%
-3.22%	12.23%	15.45%	13.84%
-3.19%	37.96%	41.16%	39.56%
-0.90%	46.76%	47.66%	47.21%
-4.45%	18.91%	23.36%	21.14%
-1.32%	54.35%	55.67%	55.01%
2.35%	60.09%	57.74%	58.91%
-5.90%	42.44%	48.34%	45.39%
-35.62%	-38.71%	-3.10%	-20.91%
-22.96%	-45.95%	-22.99%	-34.47%

Note on Nomenclature

Originally this report covered a number of different analytical approaches to the problem at issue and had a very complex nomenclature system to support and differentiate that multiple model analysis approach. When it was decided to report only the findings of the rationalized analysis, much of this complex nomenclature system became redundant. However, since the work was originally done under it, some residual vestiges of it remain.

For the purposes of this report three sets of nomenclature symbology are used, each with its own meaning and/or definitional use: [21]

1. The R, B, G, Y... etc. refer to generic receptor field parameters (normally generic field energy values for them).

2. The $X, Y, Z, S; X(\lambda), Y(\lambda)$, ... and $\int X(\lambda), \int Y(\lambda)$, ... refer to values in the C.I.E. standard system; the $\int X(\lambda), \int Y(\lambda)$, ... symbology is also used to designate the non-rationalized filter transformation energy values for the filter curves.

3. The $\mathcal{B}, \mathcal{R}, \mathcal{Y}, \mathcal{S}$ refer to rationalized filter transform energies, rationalized receptor field values, or the transform curves that generated them. The three uses are considered self-evident and therefore not differentiated by subscripts, prime marks or parenthetical functional designators.

[21] This does not include Appendix C, which uses its own independent nomenclature system.

DISCUSSION OF ANALYSIS AND FINDINGS

The following discussion divides the data into domain groups. If one takes the experimental data and calculates the receptor field energization levels as shown in the last four columns of Table 6 and graphs them against the various measured performance parameters for the test subject, one at first finds they produce a jumble of not very correlatable results. However, if one looks more deeply at the data and their movement pattern, one finds that the data divide into three distinct groups, based on the spectral energy composition exciting the color vision system of the eyes and the resulting visual performance of the test subjects. These experimentally derived performance groups consist of the following groups:

1. **X dominant group** consisting of data points 802, 805, 806, 807, 809, 810, 811, 813, 815, 817, 818, 819, 871, and 878, where the combined Red and Green Cone excitation energies are the dominant spectral energy element exciting the test subject's color vision system.

2. **N dominant group** consisting of data points N (Normal), 825, 826, 828, 830, 832, 834, and 837, where the spectral energies exciting the test subject's color vision system are essentially equal and no single cone excitation energy level is singly overridingly dominant.

3. **Z dominant group** consisting of data points 841, 842, 849, 850, 851, 855, 856, 857, and 858, where the blue cone excitation energy is the dominant spectral energy element exciting the test subject's color vision system. In this case dominant means that Z energy is greater than 42% of the total spectral energy available to the color vision system and/or more than 12% greater than either of the other two spectral energizing elements.

This grouping is not intuitively obvious from the energization levels themselves and was ultimately arrived at through trial and error by purely empirical means, based on movement in the performance effect. In this the internal relationship in group movement patterns is the key identifying parameter. (The theoretical reason for the grouping was subsequently investigated and a working hypothesis arrived at (see following discussion).) The domain groupings do however show a logical consistency, if one plots the data on a ternary percentage graph and divides them into the respective domain segments based on the data point grouping as shown in Figure 41.

Each of these groups was found to function according to its own unique rules with regard to the visual performance factors (the derivation and explanation of which comprise the bulk of the following report).

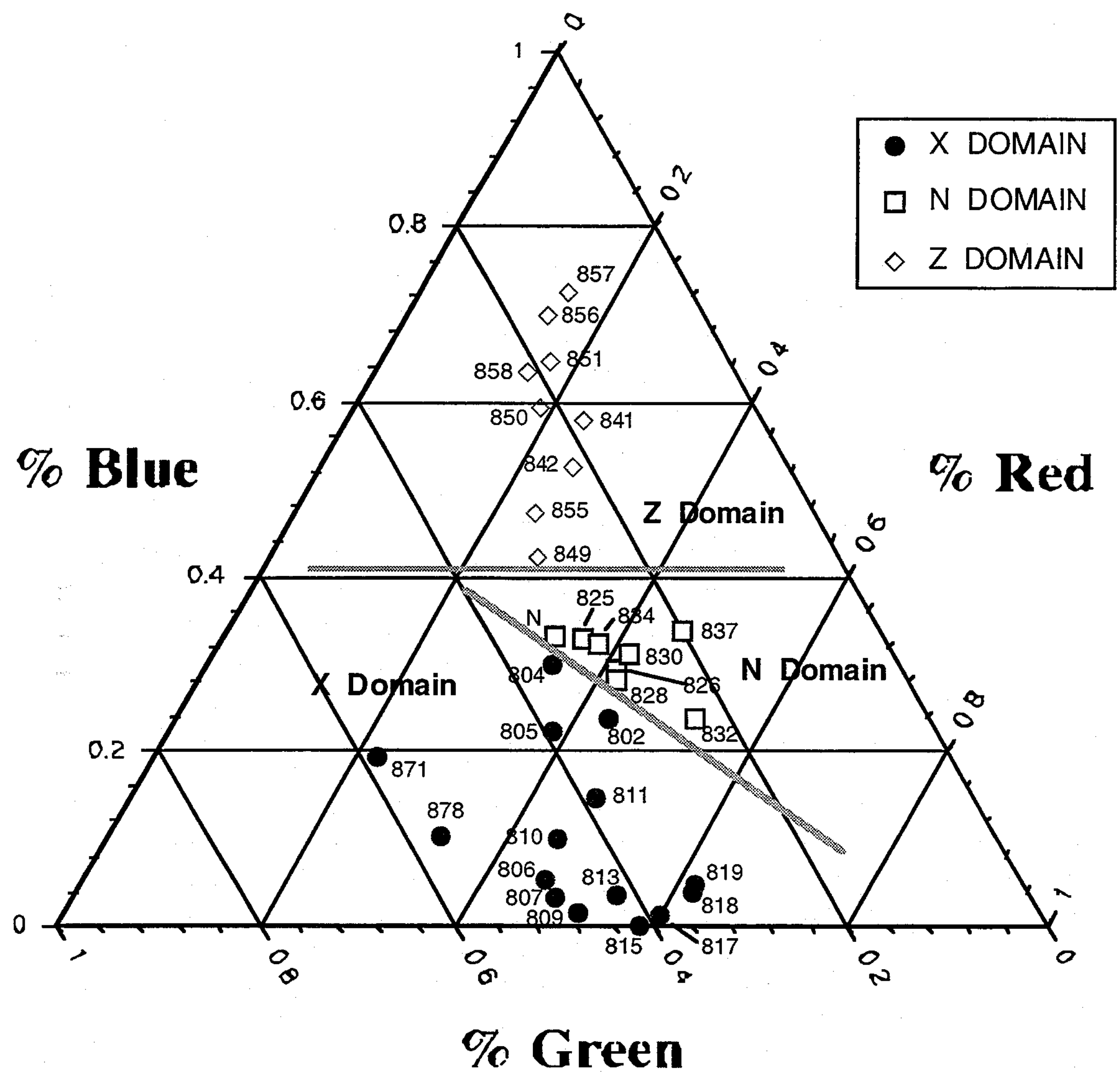

FIGURE 41. Ternary Percentage Plot Showing Dominance Domains.

GROSS PERFORMANCE VARIATION OF DOMAIN GROUPS

If one looks at the gross performance variation of the three previously identified domain groups, one finds that even the gross performance of the three groups is quite different. If one looks at gross reading speed for the three domain groups, one finds it to be as shown in the perceptual distribution diagram of Figure 42. One can see from the chart that reading speed improves in a very skewed manner in the X dominant domain group, while in the N domain group, it deteriorates in an equally skewed manner. The Z dominant domain, on the other hand, shows that while it has a slightly higher mean and is somewhat positively skewed, its gross performance improves significantly less than that of the X dominant domain group.

The statistical characteristics of the three domain performance groups can be (and were) worked out and statistical tests run to show that they are unique populations performing to their own performance rules, while the difference in performance characteristics for all three domains is easy to empirically observe in the reading speed performance chart of Figure 42. The statistical data and test result are of use in ascertaining the parameters of the gross difference in performance and are presented in the reading speed column of Tables 7 and 8.

In reality, reading performance does not appear to be an independent variable, but a dependent variable based on the performance of other factors. Two parameters that were measured in this test in a quantitative manner were angle of eye span and focal length. These two parameters show marked correlation to reading speed performance (see the following discussion of interaction) and exhibit similar domain group gross performance interrelationship among themselves. This can be seen for the angle of eye span in Figure 43, where it can be seen that for the X dominant domain, the distribution is significantly skewed upward, an essentially decreasing skewed distribution is in the N domain, and a more moderately upward skewed performance distribution for the Z domain does not reach to the same level of ultimate performance as that of the X dominant domain. (The distribution reaches a performance improvement level of only 183.7% versus the 242.1% that occurs in the X dominant domain.) X dominant domain and Z dominant domain groups have essentially the same mean, a fact that may or may not be significant but is worthy of note. The statistical data and test results for the gross difference in angular vision performance between the domain groups are presented in Tables 7 and 8 as they were for reading speed.

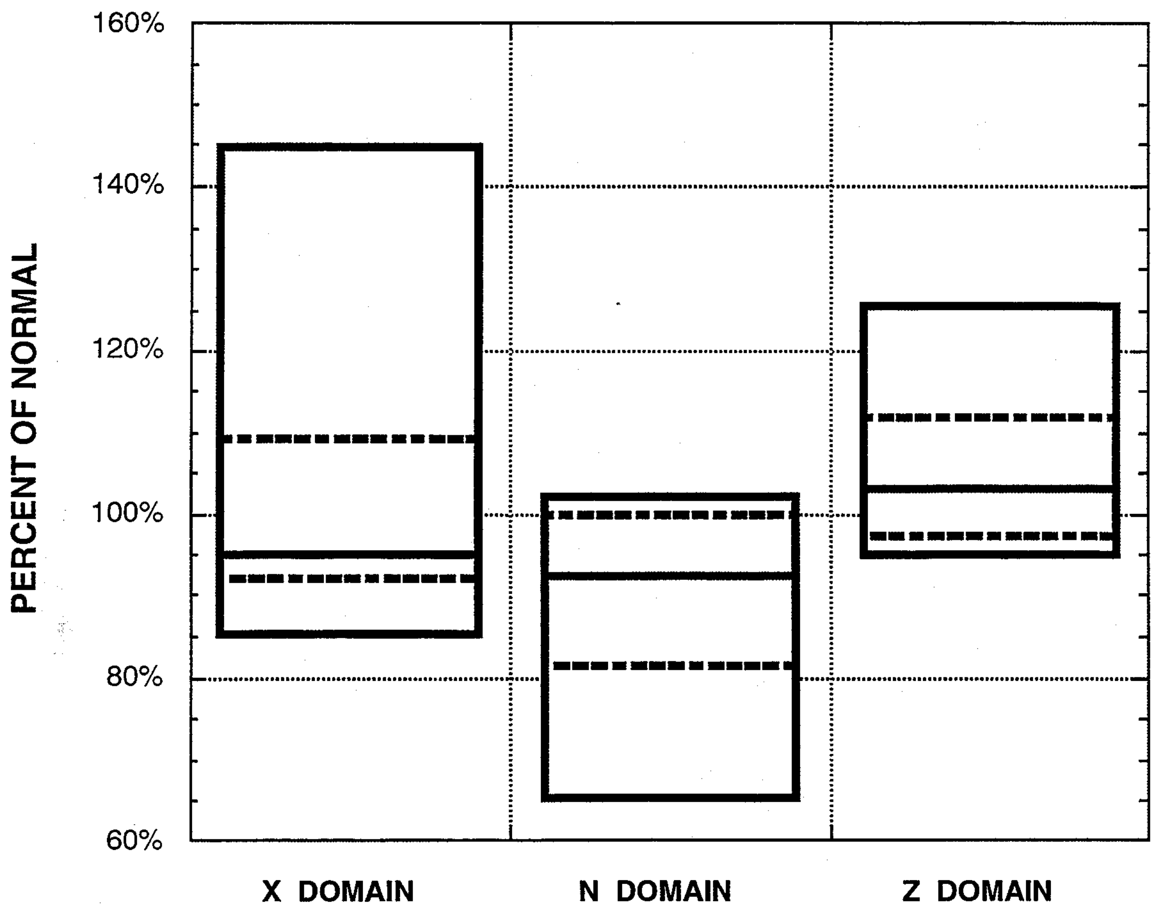

FIGURE 42. Change in Reading Speed Per Domain.

TABLE 7. Statistical Attributes of Domain Groups.

Statistical attribute	Reading Speed			Angle of Eye Span			Focal Length		
	X dominant domain	N dominant domain	Z dominant domain	X dominant domain	N dominant domain	Z dominant domain	X dominant domain	N dominant domain	Z dominant domain
Max	144.8%	102.0%	125.6%	242.1%	108.3%	183.7%	107.6%	121.8%	111.5%
Min	85.4%	65.2%	95.0%	58.4%	41.5%	59.8%	89.9%	100.0%	87.1%
Average	103.8%	89.7%	105.0%	130.1%	75.8%	116.9%	99.6%	111.3%	100.6%
Median	95.0%	92.4%	103.4%	107.8%	82.1%	109.9%	99.8%	111.5%	99.8%
Geometric Mean	102.7%	89.0%	104.6%	119.0%	71.8%	109.7%	99.4%	111.0%	100.3%
Standard Deviation	16.9%	11.7%	9.5%	58.2%	25.0%	42.0%	4.9%	8.2%	7.6%
Average of Deviation	12.7%	8.3%	7.3%	48.0%	20.9%	33.0%	3.7%	7.1%	6.2%
Skew	1.4539	-1.4185	0.9585	0.8190	-0.2384	0.1947	-0.2608	-0.1220	-0.1407
Variance	0.0285	0.0138	0.0090	0.3384	0.0623	0.1763	0.0024	0.0068	0.0058

TABLE 8. Statistical Test Results for Domain Groups.

Statistical Test		Reading Speed	Angle of Eye Span	Focal Length
T-TEST for DOMAIN GROUPS				
T-TEST for X Vs. N		0.0299	0.0054	0.0043
T-TEST for X Vs. Z		0.0095	0.0166	0.0116
T-TEST for N Vs. Z		0.0095	0.0166	0.0116
F-TEST for DOMAIN GROUPS				
F-TEST for X Vs. N		0.3366	0.0315	0.0873
F-TEST for X Vs. Z		0.0722	0.3031	0.1203
F-TEST for N Vs. Z		0.5207	0.1808	0.7946
MEAN DISTANCE TEST				
$M_X \xrightarrow{\sigma_X} M_N$	$in\ \sigma_X$	0.1539	0.4406	-2.4057
	in statistical %	6.1%	17.0%	-49.2%
$M_N \xrightarrow{\sigma_N} M_X$	$in\ \sigma_N$	-0.6514	-0.4767	2.4057
	in statistical %	-24.26%	-18.32%	49.19%
$M_N \xrightarrow{\sigma_N} M_Z$	$in\ \sigma_N$	-0.9376	-1.1108	1.4172
	in statistical %	-32.58%	-36.67%	42.18%
$M_Z \xrightarrow{\sigma_Z} M_N$	$in\ \sigma_Z$	1.1610	0.6605	-1.5325
	in statistical %	37.72%	24.55%	-43.73%
$\overline{M}_Z \xrightarrow{\sigma_Z} \overline{M}_X$	$in\ \sigma_Z$	0.8868	0.0500	0.0000
	in statistical %	31.24%	1.99%	0.00%
$\overline{M}_X \xrightarrow{\sigma_X} \overline{M}_Z$	$in\ \sigma_X$	-0.4976	-0.0361	0.0000
	in statistical %	-19.06%	-1.44%	0.00%
SIGMA RATIO TEST				
σ_X/σ_N		1.439	2.330	0.589
σ_N/σ_X		0.695	0.429	1.697
σ_N/σ_Z		1.238	0.595	1.081
σ_Z/σ_N		0.808	1.682	0.925
σ_X/σ_Z		1.782	1.385	0.637
σ_Z/σ_X		0.561	0.722	1.570

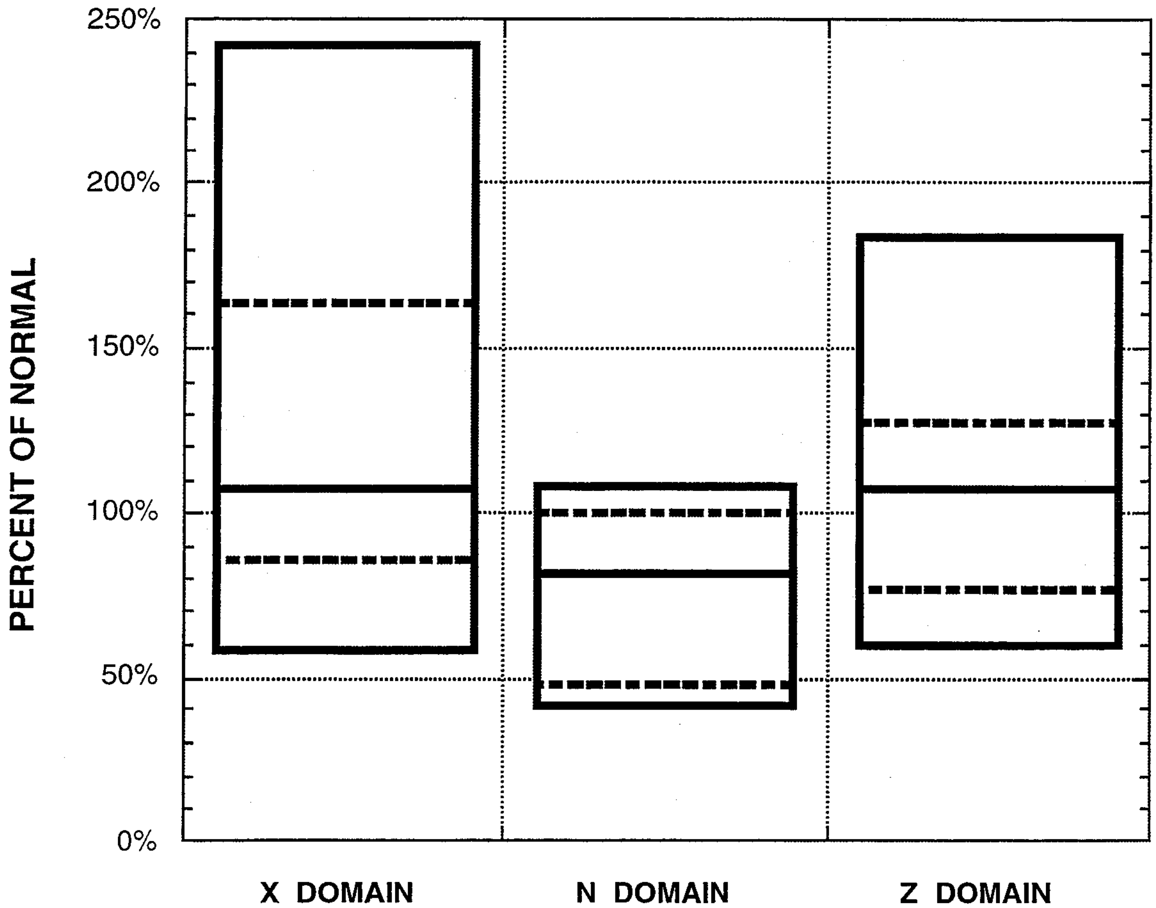

FIGURE 43. Change in Angle of Eye Span Per Domain.

The other performance factor that was definitively measured in this experiment was focal length. This factor showed much the same pattern with the three domain groups exhibiting different and essentially independent performance characteristics from one another as seen in Figure 44. In the case of focal length, the X dominant domain is grouped more or less symmetrically about its mean with the narrowest total swing of the three groups. The N domain group increase has, as a whole, a much longer focal length, always in fact longer than normal, and no points that have shorter than normal focal lengths. While the Z dominant domain group has the largest overall range of the three groups and is by no means statistically symmetrical, one point that is worth noting is that the means of the X dominant domain group and the Z dominant domain group are essentially equal to each other and are both essentially equal to normal—a fact that is very significant. The general statistical data on the focal length groups are likewise presented in Tables 7 and 8.

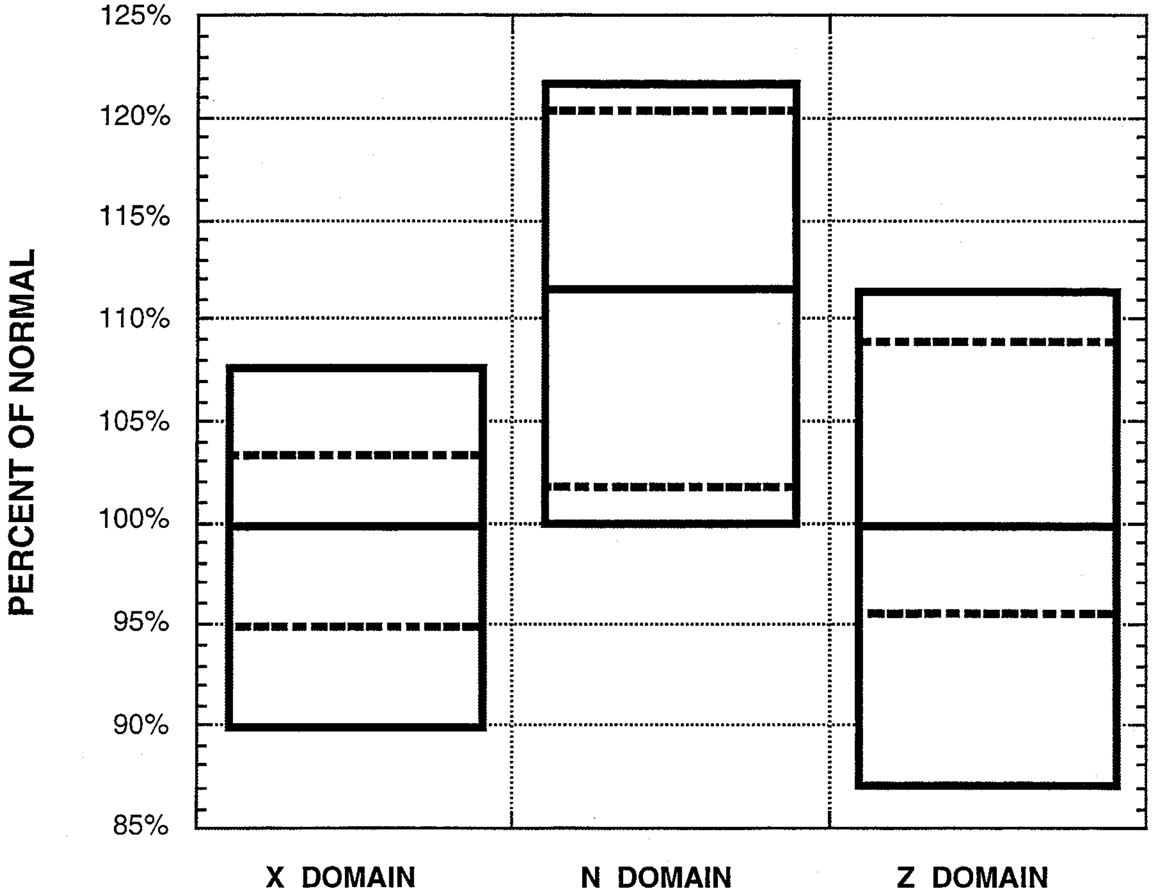

FIGURE 44. Change in Focal Length Per Domain.

The important fact in the preceding discussion is not the gross performance of the groups as such, for that is actually controlled by a complex interrelationship within and between receptor fields (which is discussed in detail below), but that the three groups represent distinct populations that are acting differently from each other and according to their own distinct rules.

Subsequent analysis shows that there may actually be more than three groups, with the major groups dividing into subgroups (see the following discussion in Reasons for Performance Grouping). However, the current experimental database is really insufficient to determine this, and it would require a more comprehensive experiment to determine the existence and influence on performance of these subgroups. From the existing experimental data all one can say is that subgroups may exist. It would also appear, for the purposes of this experiment, that the influence of subgroups, if they do exist, is much more subtle than that of the major grouping divisions, ranging from 9.5% to 2% (which is felt to be below the error limit of the experiment in most cases). This may really be a weight of data problem, for it turns out that most of the

potential subgroups are represented by only one to three data points. In reality it is very hard (to put it mildly) to run a meaningful statistical analysis involving such a limited number of data points. (If one tries to use high-grade statistical tests on these limited data arrays (which was tried in several cases), the best one can come up with on these data is a firm maybe.) As a result the empirical three-part division evident in the data will be used as the basis for the following discussion and analysis.

EFFECT OF SPECTRAL ENERGIZATION ON RECEPTOR FIELD PERFORMANCE

As noted, it is not receptor field performance that is really important, nor is gross domain group performance a particularly useful attribute. In point of fact, one probably cannot determine "gross performance" of the domain groups, or even the existence or composition of the domain groups, without knowing what is happening in the receptor field energization plots themselves. Gross visual performance is really merely a reflection of what is happening to the individual data points themselves in their domain group in the receptor field energization level plots. It is the performance relationship and movement of the points within the domain group receptor field energy plots that are actually the important and controlling events.

The really important relationships turn out to be data-point movement in the various receptor fields, domain group and their relationship to each other and spectral energy movements. Because of the amount of data and analysis involved, discussion of this is done by performance variable in the following order: Reading speed, angle of eye span, and focal length, with an attempt to analyze the performance of each domain group versus each performance variable.

READING SPEED PERFORMANCE VERSUS RECEPTOR FIELD ENERGY LEVEL

The most striking finding of this study is that the visual performance of this Irlen-type dyslexic test subject is directly proportional to the level and sign of the spectral energization of a given receptor field, which is divided up into domain groups as noted in the preceding text, with each domain group apparently obeying its own unique set of performance rules, which depend on energy level and sign of the output produced in a given type of receptor field.

This relationship is clearly evident in raw Reading Speed versus $\mathcal{B}$-$\mathcal{G}$ Receptor Field energy level plot of Figure 45.

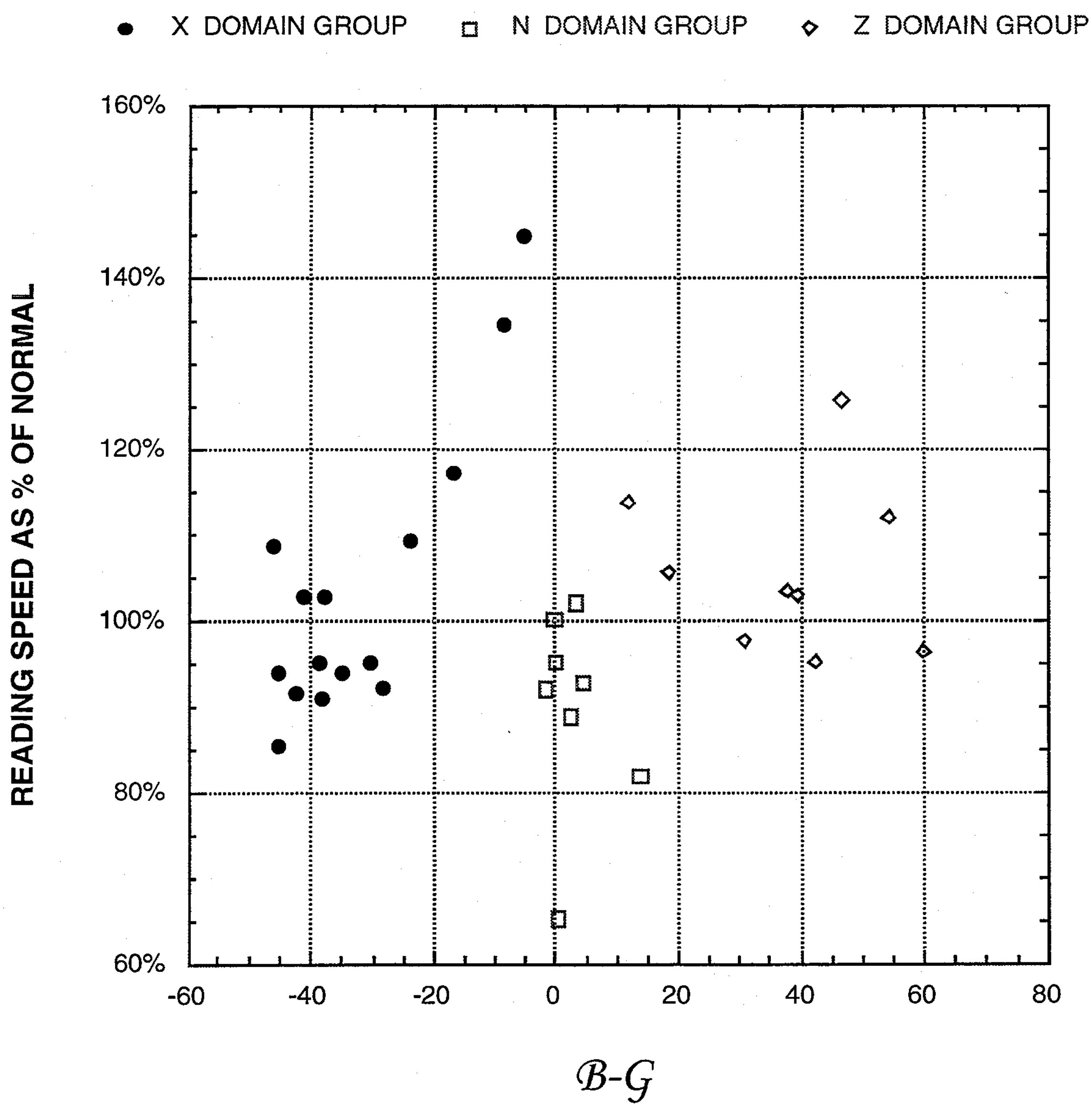

FIGURE 45. Rationalized ℬ-𝒢 Receptor Field Energy vs. Reading Speed.

Domain Groups

The three domain groups form coherent data groups on the plot. (They also move as coherent groups maintaining their group interrelationship between field plots, as is seen in the following analysis.) In the case of the $\mathcal{B}$-$\mathcal{G}$ reading speed plot, the subject's reading speed increases markedly as $\mathcal{B}$-$\mathcal{G}$ becomes less negative, for the X dominant domain group. This relationship has a high statistical correlation (0.84) and represents an increase of 107.8% reading speed for every 1% change in $\mathcal{B}$-$\mathcal{G}$ negative energy level. At the same time, the N domain and Z domain dominant groups appear to be either unaffected by changes in $\mathcal{B}$-$\mathcal{G}$ energy level or random noise. (For correlation factors, see the General Correlation Chart of Table 9.)

On the other hand, for the $\mathcal{B}$-$\mathcal{R}$ Receptor Field energy plot shown in Figure 46, while the general performance groups hold together, the relationship changes somewhat. The performance improvement relationship of the X dominant group still holds true, admittedly with a lesser degree of correlation (0.63, the N domain group now shows a marked correlation (0.844) with reading speed getting better as the $\mathcal{B}$-$\mathcal{R}$ energy becomes less negative or reading speed becoming worse as $\mathcal{B}$-$\mathcal{R}$ becomes more negative, if one prefers to express it that way). At the same time, the Z dominant domain still appears to be random noise showing no effective change with $\mathcal{B}$-$\mathcal{R}$ energy level.

These general relationships hold true for the $\mathcal{B}$-$\mathcal{Y}$ energy plot of Figure 47, admittedly at a slightly lower correlation level than in the $\mathcal{B}$-$\mathcal{G}$ energy plot, as can be seen in Table 9 (which one might expect since $\mathcal{Y}$ is a combination of $\mathcal{G}$ and $\mathcal{R}$).

On the other hand, if one looks at the $\mathcal{R}$-$\mathcal{G}$ energy plot of Figure 48, one finds that the X dominant domain group appears to be nothing more than distributed random noise. Although one can claim that, intuitively, what one is seeing is the result of multiple correlations, mathematical justification does not exist for that hypothesis, and no definite relationship to justify it could be found in the existing data set. The negative relationship between reading speed and increasing positive energy for the N dominant domain group has a strong correlation (0.84).

TABLE 9. General Correlation Chart.

Performance factor	Dominance group domain	Effect on			
		R-G	B-G	B-R	B-Y
Reading speed	X	-0.0736	0.8407	0.6313	0.8203
	N	-0.8410	-0.1753	0.8441	0.6383
	Z	-0.1566	-0.1045	-0.0690	-0.0879
Focal length	X	0.0640	0.3961	0.2105	0.3269
	N	0.5781	-0.2842	-0.4890	-0.2826
	Z	0.0751	-0.7105	-0.7664	-0.7436
Angle of eye span	X	-0.3530	0.6766	0.7668	0.8374
	N	-0.1682	0.5475	0.4935	0.6830
	Z	-0.5885	-0.7518	-0.6365	-0.7011

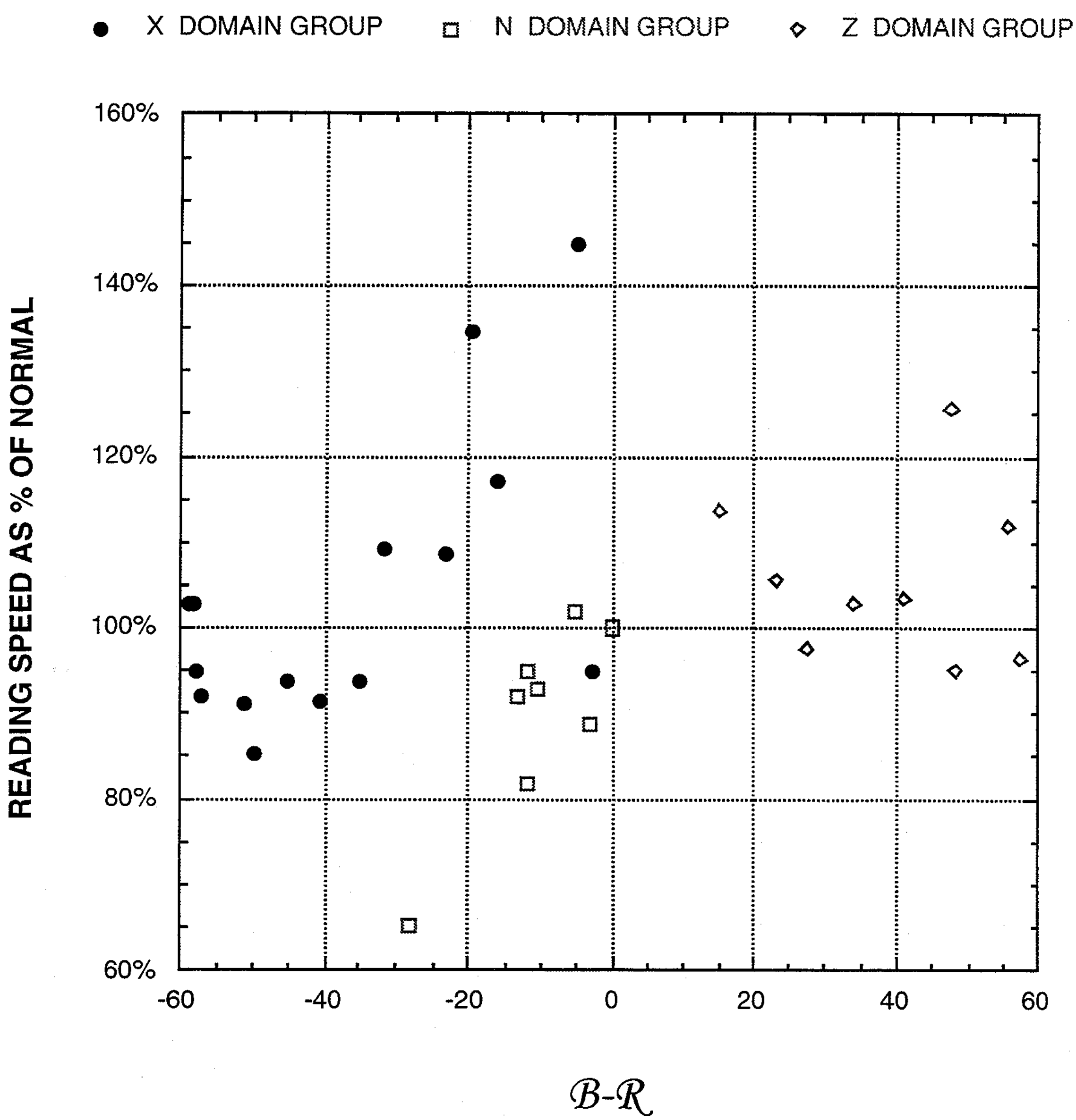

FIGURE 46. Rationalized ℬ-ℛ Receptor Field Energy vs. Reading Speed.

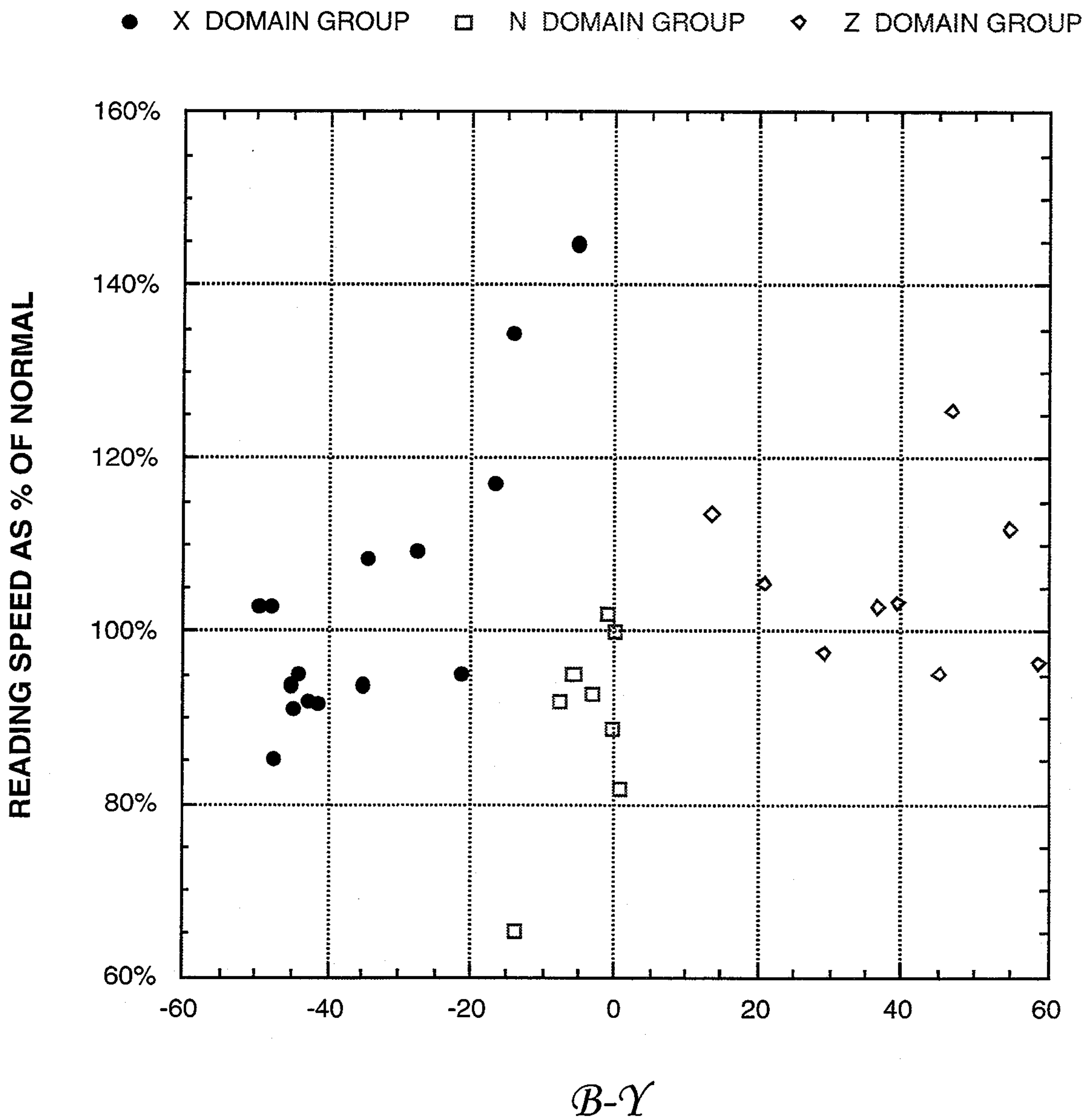

FIGURE 47. Rationalized ℬ-𝒴 Receptor Field Energy vs. Reading Speed.

The most interesting pattern in the $\mathcal{R}$-$\mathcal{G}$ energy plot, however, is for the Z dominant domain group, which if one runs blind statistical correlation on it says that it has no correlation (-0.1566). However, if one looks at it, one sees that separate groups are apparently on the positive and negative side of $\mathcal{R}$-$\mathcal{G}$=0. If this two-group hypothesis is tested, one finds that the two groups, if treated independently, have correlations of 0.87 for the negative side group and 0.98 for the positive side group, which would lead one to conclude that they are in fact independent groups. (For a discussion of this phenomenon, see that discussion of the possibility of subgroups in the next section.)

Summary of Reading Speed Findings

Based on the above Receptor Field analysis, one would conclude the following:

1. The reading speed performance is a function of which domain group the spectral energy energizing the eye's vision system is in.

2. The individual domain groups act in a very tightly controlled manner in relationship to reading speed.

3. The controlling relationship for reading speed is an individual data point's energy level within a given Receptor Field and domain group.

4. Certain receptor fields seem to have a controlling influence over certain domain groups and no influence over others.

5. The domain groups tend to hold together and act as a unique array set of points regardless of which receptor field they are plotted in.

6. Raw reading speed tends to improve as the energy level of controlling receptor field approaches zero.

It would appear that data points on different sides of zero for a controlling receptor field act in accordance with a different set of performance rules in regard to raw reading speed, depending upon whether they are on the plus side or the minus side.

In most cases (the Z dominant domain group being the exception), data points are apparently controlled on only one side of zero in a domain group in a receptor field and that the data points on the other side of zero are not influenced and/or controlled by it. (This may, however, be a false appearance resulting from not having sufficient data points in the right energy domain on the other side in this experiment.)

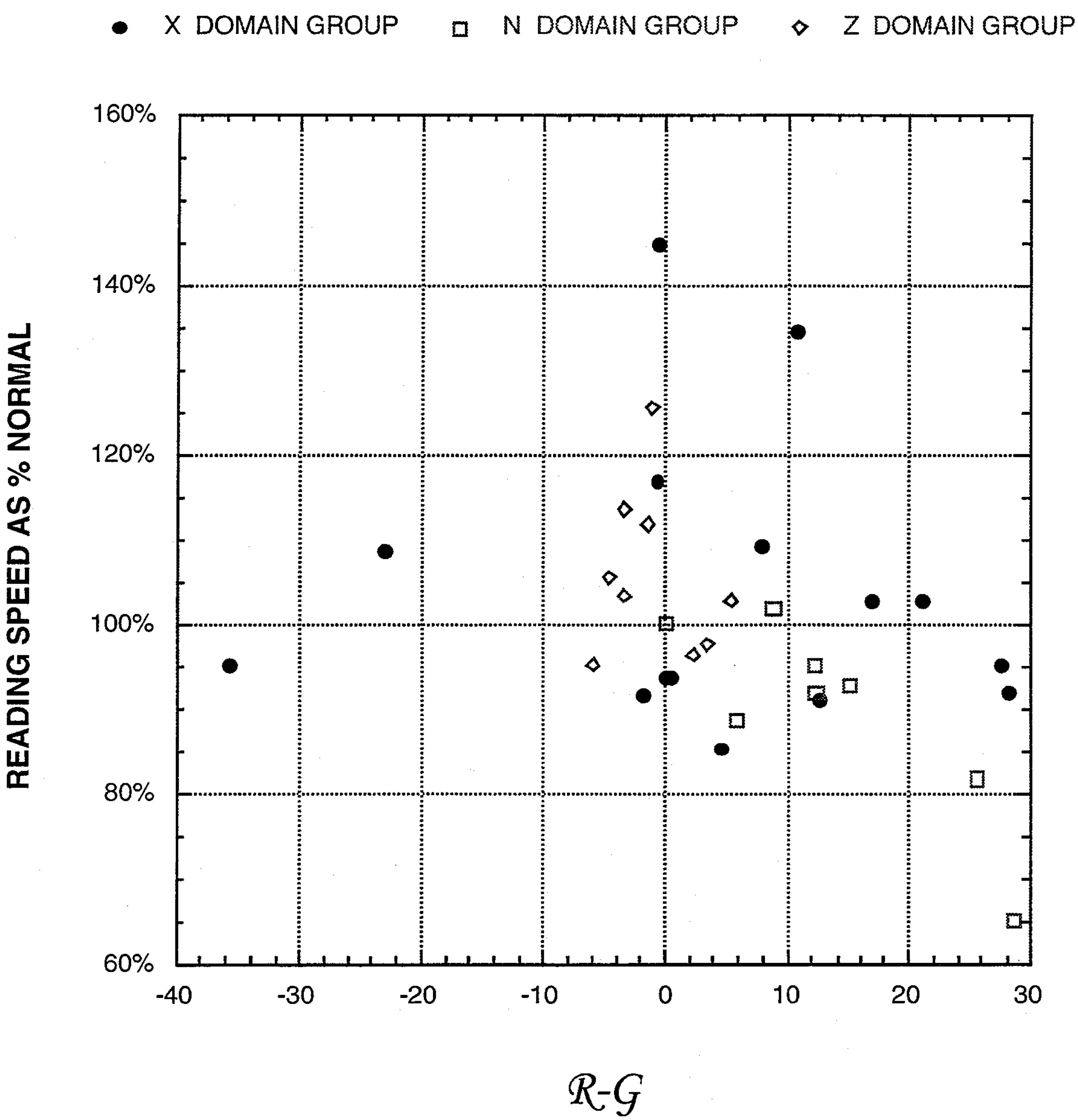

FIGURE 48. Rationalized ℛ-𝒢 Receptor Field Energy vs. Reading Speed.

COMMENT IN RELATION TO IRLEN HYPOTHESIS

The experiment in effect vindicates Irlen's hypothesizes that the energy spectrum of light presented to the vision system of dyslexics is capable of affecting their visual performance in the form of raw reading speed. She is also correct in that by selective modification of the spectral energy composition of light reaching the subject's eye, one can improve reading performance markedly (one can also make it worse).

This experiment, however, shows that Irlen does understate the complexity of the underlying phenomenon in that the improvement in reading speed depends on the placement of the modified energy spectral input being in both a given dominant domain and its energy level within a given receptor field of the eye's visual system.

CAUSES OF READING SPEED VARIATION

One of the findings of this study is that the variation of raw reading speed is not an independent variable, but is a result of, and interrelated to, the influence of both angle of eye span and focal length, two parameters that were measured by this study[22]. It would appear from this experimental data that a reasonably complex interrelationship exists between these three variables. While insufficient data may exist to fully derive the relationship from this experiment, a reasonable start on the relationship's basic form and parameters can be deduced from studying the other two parameters and their relationship to reading speed, as is attempted in the following sections.

ANGLE OF EYE SPAN VERSUS RECEPTOR FIELD ENERGY LEVELS

One of the phenomena found by this experiment, as noted previously, was that the angle of eye span of the test subject changed markedly depending on the composition of the spectral energy presented to the eye. This result was not really expected at the start of the test, but once found, data on the phenomenon were taken and subsequently analyzed. When this angle of eye span data were subjected to the same type of receptor field analysis just used on reading speed, the findings of this analysis showed that the dominant performance groups still act as a set and move together in a coherent manner in the various receptor field plots.

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[22] A couple of factors not measured by this experiment (namely, quantity and quality of light) may also affect the ultimate outcome, but the existing experimental database is insufficient to verify that hypothesis.

The receptor field plots for angle of eye span show a somewhat different correlation pattern than those for reading speed in that for all $\mathcal{B}$ inclusive plots ($\mathcal{B}$-$\mathcal{G}$, $\mathcal{B}$-$\mathcal{R}$, and $\mathcal{B}$-$\mathcal{Y}$), both the X dominant and Z dominant domain groups show positive correlations, better angle of eye span, with lower receptor field energy levels. If one looks at the receptor energy plots themselves (Figures 49, 50, and 51), one finds that while the X dominant domain is somewhat more ragged than in the reading speed plots. It still shows the same general trend of improving (in this case, increases) as the receptor field energy level becomes less negative. On the other hand, the Z dominant domain energy plots exhibit an entirely different pattern in these three $\mathcal{B}$ plots than they did on the reading speed plots (where they showed up as essentially random noise). In the Angle of Eye Span vs. Receptor Field energy plots, they show up with relatively high correlations of improving performance as receptor field energies become less positive.

The correlation numbers for both these energy domains are quite high, as can be seen in the General Correlation Chart in Table 9. (These correlation factors become much higher if the known potential subgroup data are removed and/or factored out, as can be seen in Table 10, which shows the correlation with the suspected subgroups removed, where the correlation factors for these items in some cases reach into the 0.9 range.) If one looks at angle of eye span for the X dominant and Z dominant domains for $\mathcal{B}$-$\mathcal{G}$ as shown in Figure 52, one sees that as they approach $\mathcal{B}$-$\mathcal{G}$=0, the angle of eye span generally increases.

On the other hand, if one looks at the $\mathcal{R}$-$\mathcal{G}$ Receptor Field plot for angle of eye span, Figure 53, one sees that the X dominant domain again appears to be uncorrelated scatter, while Z dominant domain points are arranged symmetrically along the $\mathcal{R}$-$\mathcal{G}$=0 axes, a fact that makes rendering a valid judgment as to correlation and effect very difficult. Though the formal statistical analysts say probably (see Table 9), and if the possible subgroups are removed, this probability increases markedly (see Table 10).

The N domain data points for angle of eye span show only a moderate degree of correlation in the three $\mathcal{B}$ plots. In the case of the $\mathcal{B}$-$\mathcal{G}$ plot, the distribution is so vertical as to be meaningless (though the correlation does work out mathematically to a firm maybe). In the $\mathcal{B}$-$\mathcal{R}$ and $\mathcal{B}$-$\mathcal{Y}$ plot, there is a trend to increasing angle of eye span as the energy level becomes less negative, but the scatter of the points is very high. Something of the same can be said for the N domain of the $\mathcal{R}$-$\mathcal{G}$ plot where there appears to be a trend of angle of eye span improvement as the $\mathcal{R}$-$\mathcal{G}$ field energy level becomes less positive. But the spread in the data is so great that the statistical calculations say this is really questionable (see Table 9).

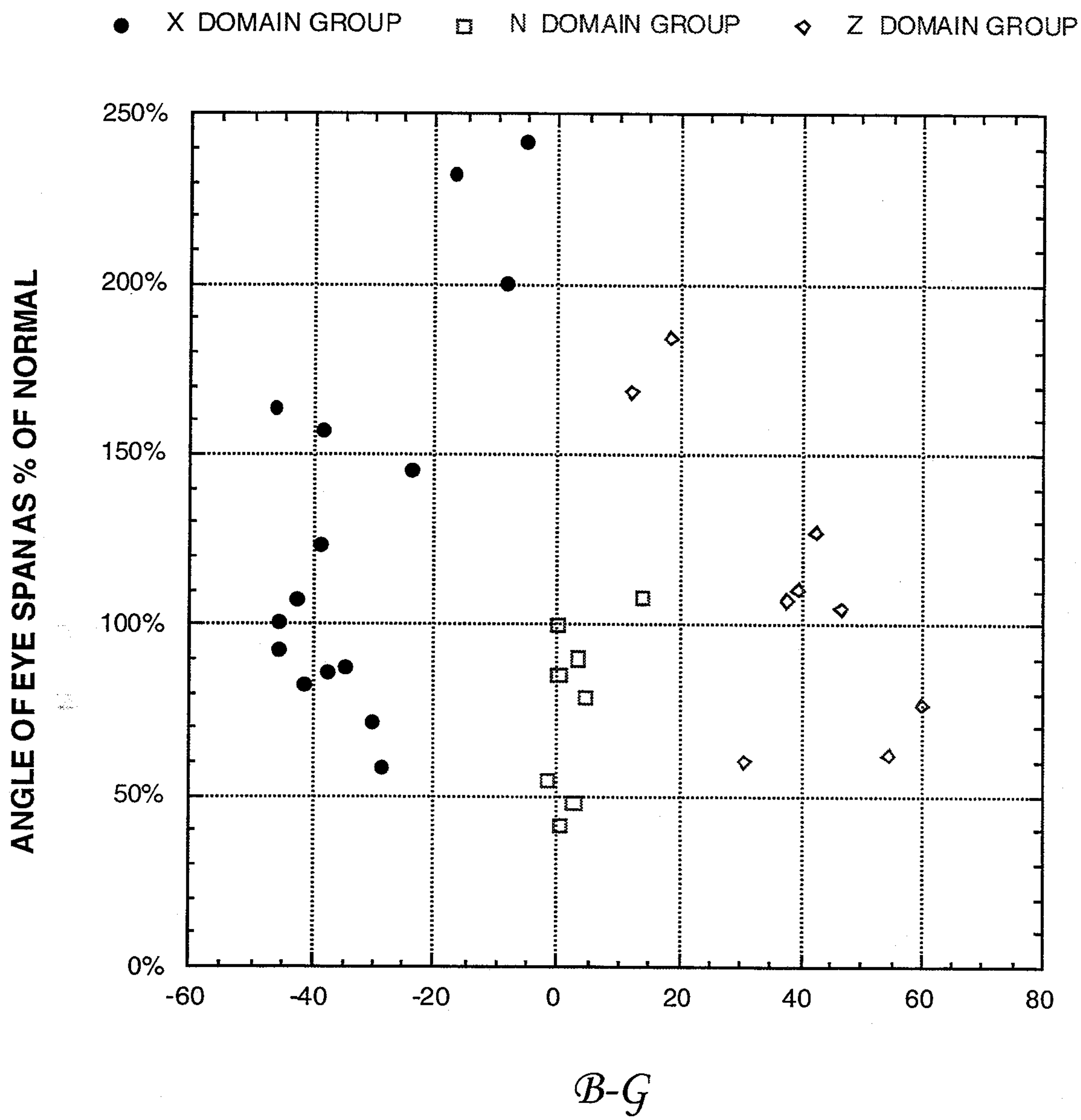

FIGURE 49. Rationalized $\mathcal{B}$-$\mathcal{G}$ Receptor Field Energy vs. Angle of Eye Span.

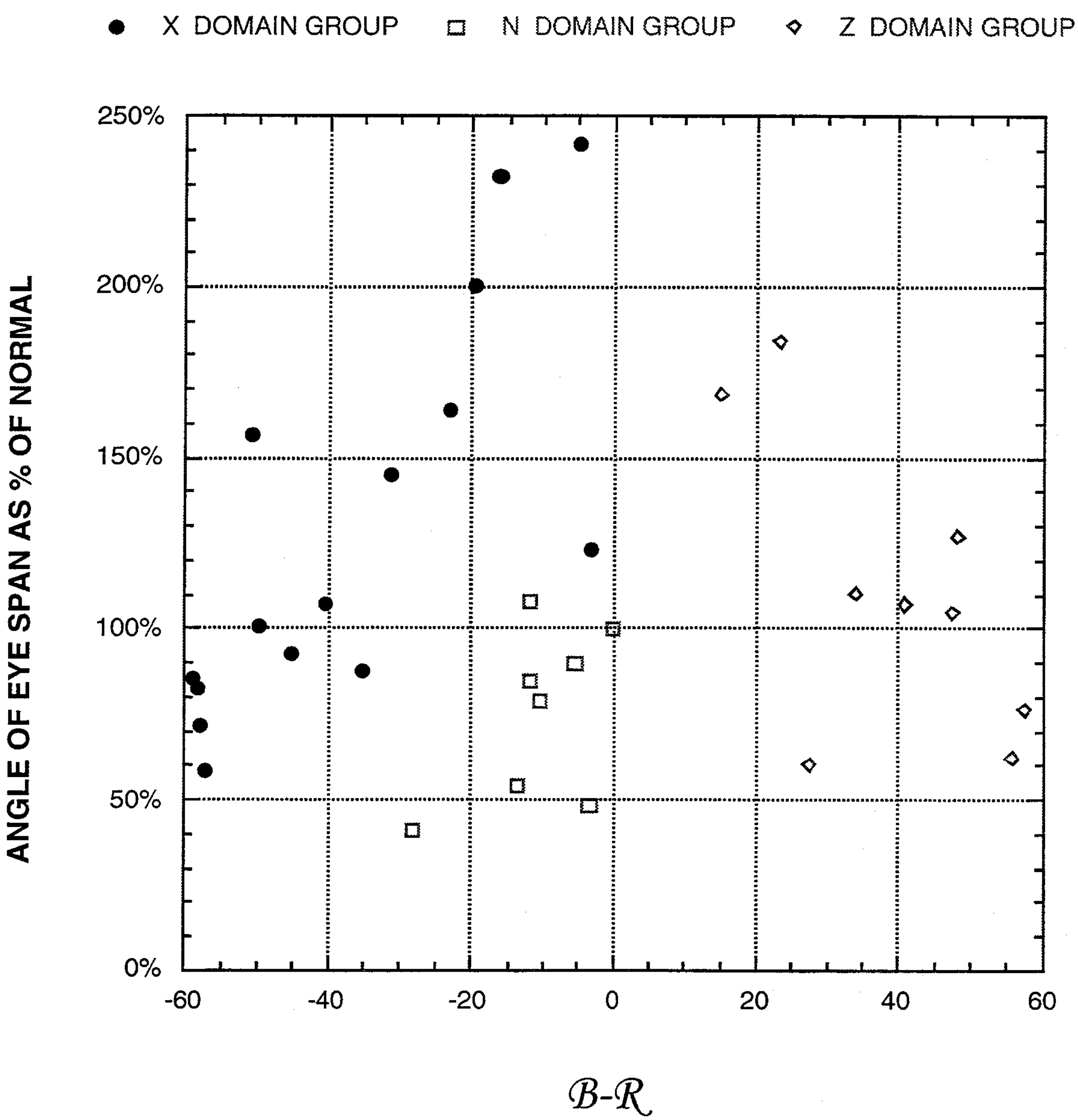

FIGURE 50. Rationalized ℬ-ℛ Receptor Field Energy vs. Angle of Eye Span.

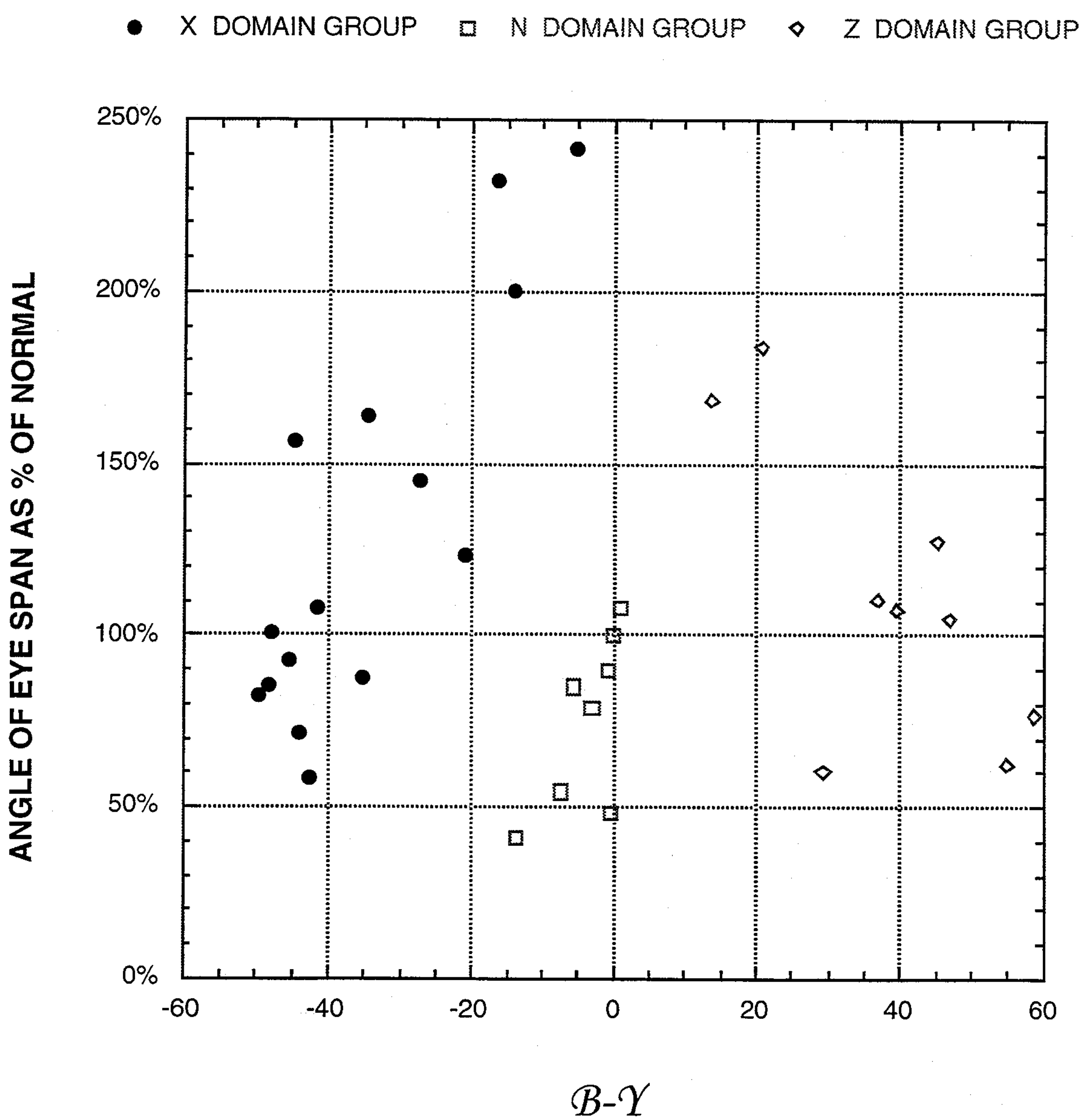

FIGURE 51. Rationalized $\mathcal{B}$-Υ Receptor Field Energy vs. Angle of Eye Span.

TABLE 10. Effect of Potential Sub-Groups on Receptor Field Correlation Factors.

Performance factor	Dominance group domain	Effect on $\mathcal{R}$-$\mathcal{G}$	Effect on $\mathcal{B}$-$\mathcal{G}$	Effect on $\mathcal{B}$-$\mathcal{R}$	Effect on $\mathcal{B}$-$\mathcal{Y}$
Reading speed	X	-0.0736 Less points 871 & 878 -0.2399	0.8407 Less points 871 & 878 -0.9028	0.6313 Less points 871 & 878 -0.8174	0.8203 Less points 871 & 878 -0.9000
	N	-0.8410	-0.1753	0.8441	0.6383
	Z	-0.1566 - SIDE 0.8716 + SIDE 0.9800	-0.1045 - SIDE 0.0960 + SIDE -0.3960	-0.0690 - SIDE -0.0037 + SIDE -0.4699	-0.0879 - SIDE 0.0473 + SIDE -0.4345
Focal length	X	0.0640 Less points 871 & 878 -0.0996	0.3961 Less points 871 & 878 -0.4333	0.2105 Less points 871 & 878 -0.3852	0.3269 Less points 871 & 878 -0.4277
	N	0.5781	-0.2842	-0.4890	-0.2826
	Z	0.0751 - SIDE 0.2793 + SIDE 0.6408	-0.7105 - SIDE -0.6696 + SIDE -0.9961	-0.7664 - SIDE -0.6654 + SIDE -1.0000	-0.7436 - SIDE -0.6685 + SIDE -0.9990
Angle of eye span	X	-0.3530 Less points 871 & 878 -0.5152	0.6766 Less points 871 & 878 -0.7725	0.7668 Less points 871 & 878 -0.8915	0.8374 Less points 871 & 878 -0.8859
	N	-0.1682	0.5475	0.4935	0.6830
	Z	-0.5885 - SIDE 0.5846 + SIDE 0.7549	-0.7518 - SIDE 0.9308 + SIDE 0.1990	-0.6365 - SIDE -0.9015 + SIDE 0.0256	-0.7011 - SIDE -0.9178 + SIDE 0.0653

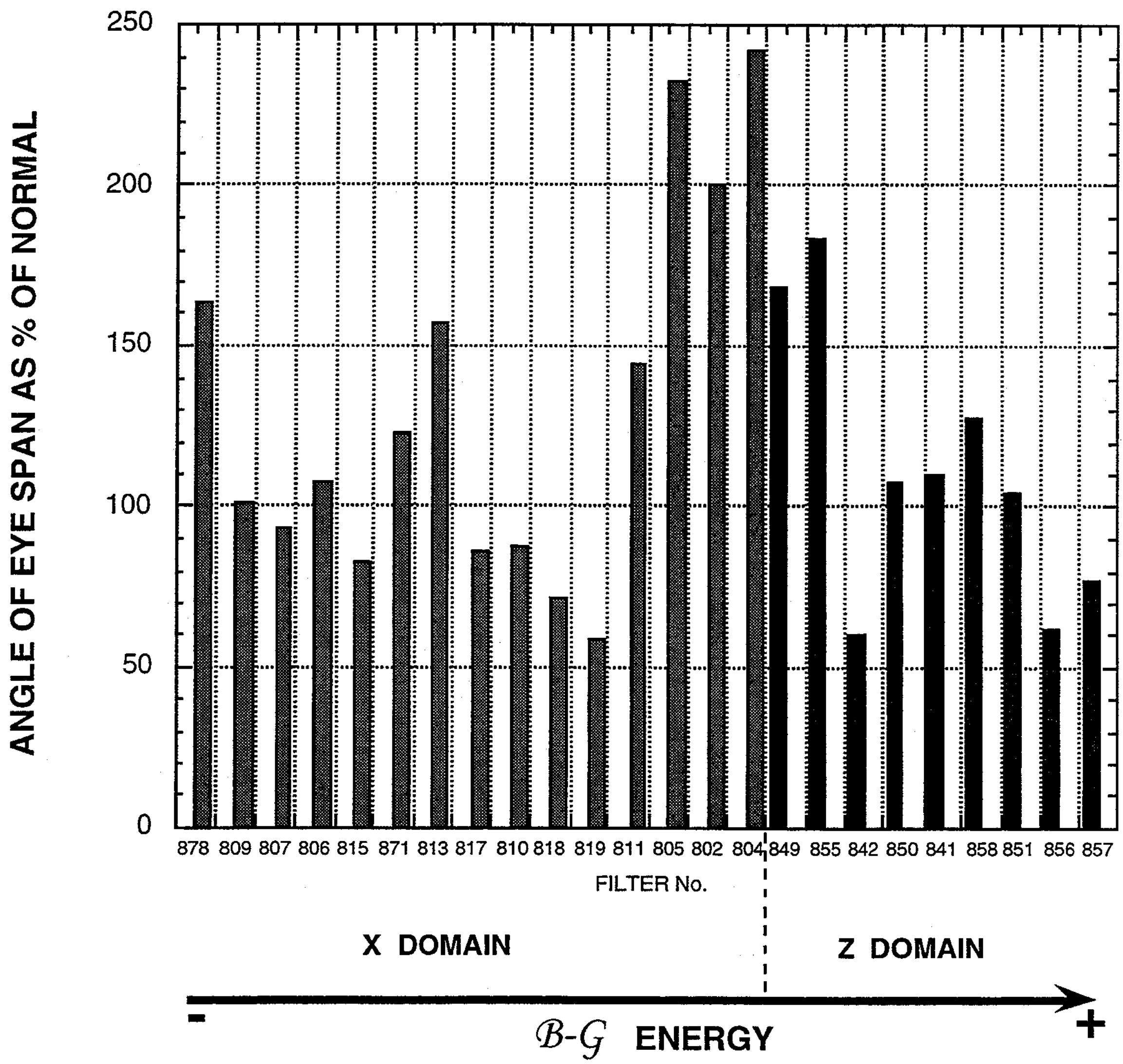

FIGURE 52. Angle of Eye Span vs. ℬ-𝒢 Energy Level.

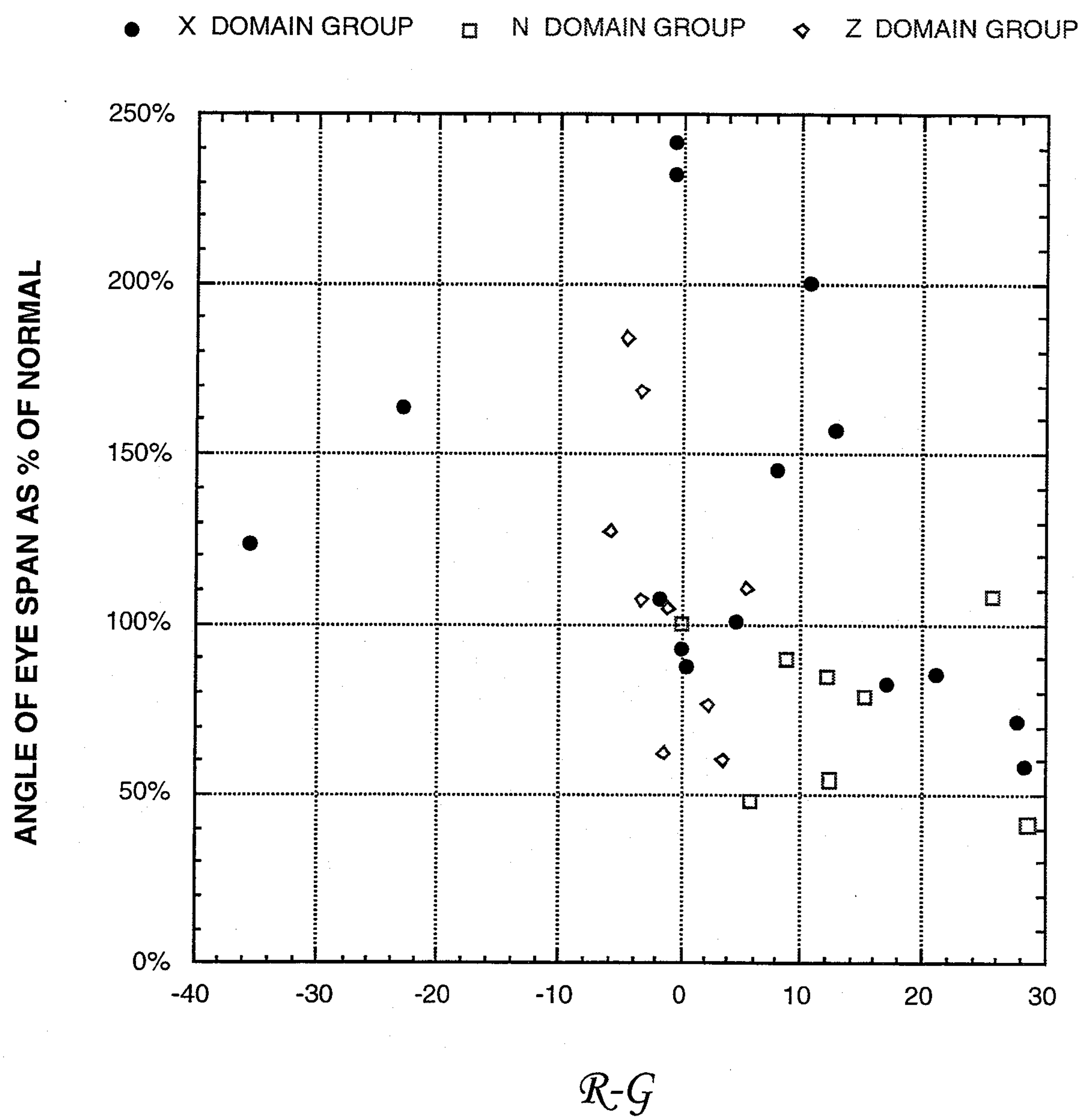

FIGURE 53. Rationalized ℛ-𝒢 Receptor Field Energy vs. Angle of Eye Span.

ANGLE OF EYE SPAN FINDINGS

If one looks at the previously presented data summaries and receptor field plots, one comes up with the following general conclusion with regard to the relationship between angle of eye span and receptor field energy:

1. The three domain groups identified earlier are still there as coherent groups and act in a coherent manner within themselves in relation to receptor field energies.

2. These three domain groups act as distinct groups with regard to visual performance, obeying their own unique rules.

3. The X dominant domain group has the greatest variation in performance varying from +242% to -41.6%. It also generates the greatest improvement, which represents a 142% increase over normal.

4. The N domain shows a general trend of deterioration with the angle of eye span deteriorating to 41.5% of normal at the bottom end of this group. In almost all cases, visual performance (as measured by angle of eye span) is worse than normal.

5. When angle of eye span is plotted against receptor field energy, it is found that the angle of eye span increases as receptor field energy approaches zero. (This is true in all cases, except the $\mathcal{R}$-$\mathcal{G}$ Receptor Field Energy plot for the Z dominant domains.)

ANGLE OF EYE SPAN VERSUS READING SPEED ANALYSIS

If one looks at the relationship between angle of eye span and reading speed, one finds that, in general, reading speed increases as angle of eye span increases. This can be seen in the general plot of Figure 54. If one breaks the three dominant groups out and plots them as individual groups as shown in Figure 55 and does individual group performance plots, one finds that the slope of the performance line of the X domain group and the N domain group are for all practical purposes parallel, with only the Z domain group having a different slope.

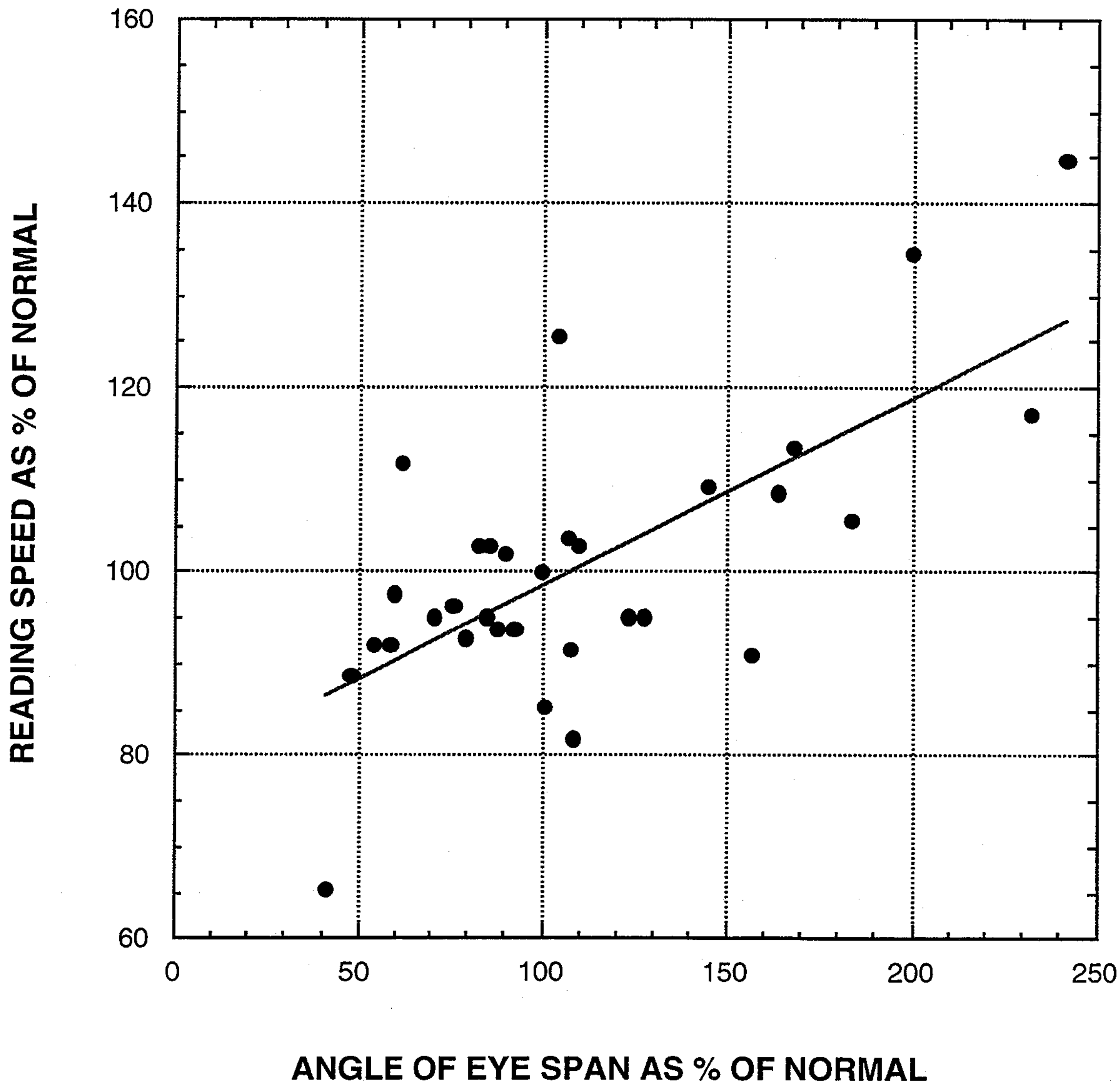

FIGURE 54. Base Interrelationship of Reading Speed and Angle of Eye Span.

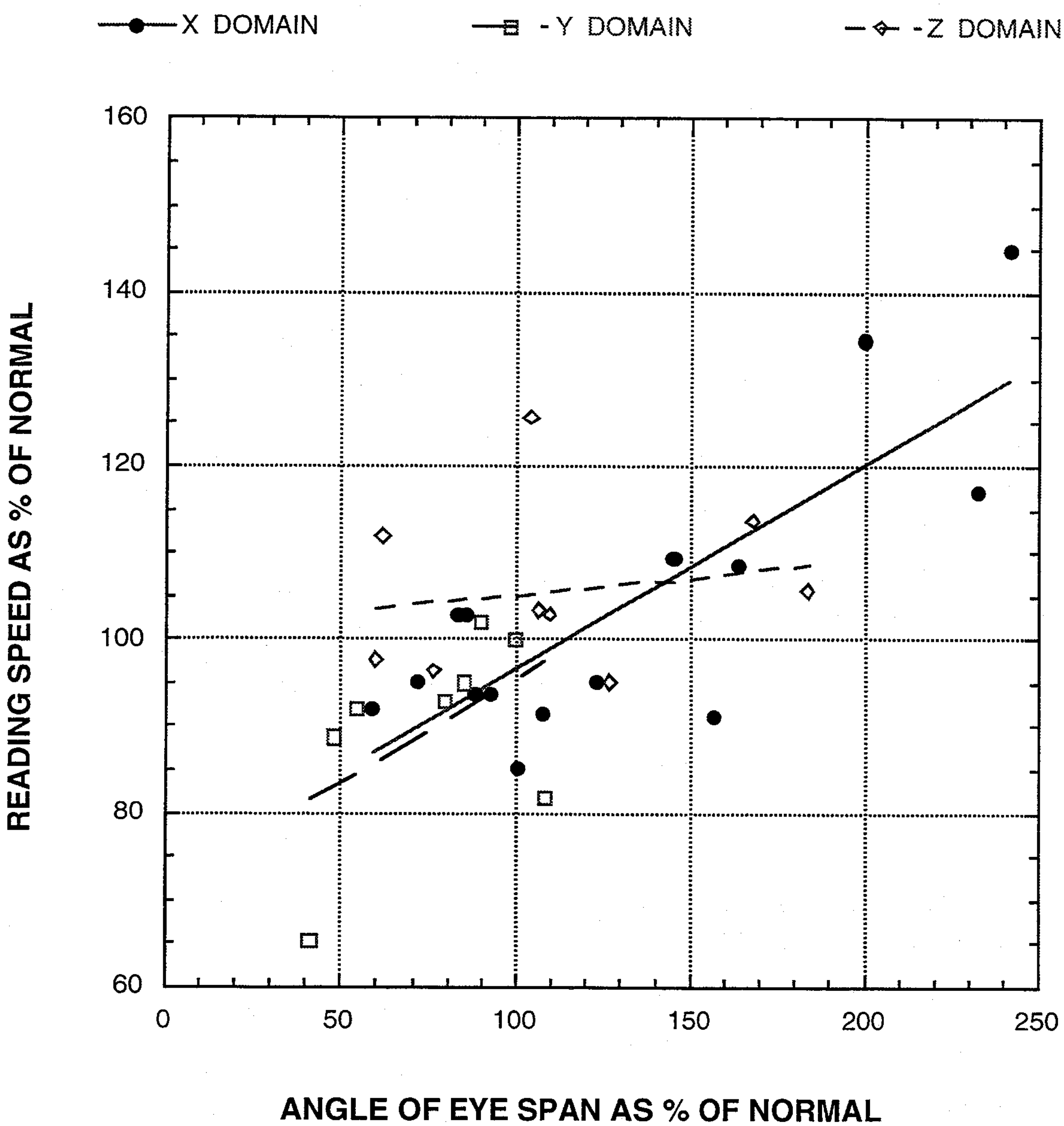

FIGURE 55. Interrelationship of Reading Speed and Angle of Eye Span by Domain Group.

The equivalence of the domain slopes was thought to be of sufficient interest to warrant further investigation. As a result, about a dozen sets of exclusion and variation studies were done on the line slopes. The results were somewhat surprising, in that most of the potential subgroups were found to have independent slopes, especially equivalent to the X and N domain line slopes. Only the positive Z points do not conform to this pattern. As a result of this, it was found that the slopes of angle of eye span versus reading speed are terribly insensitive to change, much more so than one would intuitively believe. (In point of fact, most of the subgroup inclusion/exclusion and combination tests were able to change the slope of the line by only about 2%.) (This phenomenon is felt to be significant and would probably be worth pursuing if one had a larger database.)

ANGLE OF EYE SPAN VERSUS READING SPEED SLOPE STUDIES

As part of the previously discussed attempt to find a relationship between reading speed, angle of eye span and focal length, the relationship between angle of eye span and reading speed by domain group was studied. In the process of this, the rate of increases in the X domain and N domain were found to be essentially equal, and the Z domain had a significantly different performance as a domain group. Based on this, a set of studies was done on the inclusion and exclusion of various subgroups from the domain sets. This set of studies led to consideration of the following cases:

1. All the domain works together on a common principle.

2. All points on the negative side of the $\mathcal{R}$-$\mathcal{G}$ null asymptote work together.

3. All points on the positive side of the $\mathcal{R}$-$\mathcal{G}$ null asymptote work together.

4. The three points on the positive side of the $\mathcal{R}$-$\mathcal{G}$ null asymptote work independently of the rest of the Z domain.

5. The two points on the far negative side of the $\mathcal{R}$-$\mathcal{G}$ null asymptote do not act as part of the X domain group.

6. The two points on the far negative side of the $\mathcal{R}$-$\mathcal{G}$ null asymptote act as part of the Z domain.

Upon analysis, the total difference among these cases was found to be only 9.5%. Among several, the difference was only 2%. This means that while any of the cases can be supported with equations for reading speed performance vs. angle of eye span and statistical correlation derived, the reality is that the

total results of the seven cases all probably lie within the limits of the experimental error of the data set. (Again basically too few data points lie in the wrong place.)

ANGLE OF EYE SPAN VERSUS READING SPEED FINDINGS

Basically, what we can say from this study is that

1. Reading speed generally increases with the angle of eye span, though this is not the sole constituent of reading speed. Some other factor or factors are involved.

2. The angle of eye span moves in some fixed manner, depending on which dominant group or subgroup it is in (though it is not possible to say exactly which group or subgroup is controlling, based on the present data set).

In short, while we can say from the experiment that angle of eye span expands and contracts for Irlen-type dyslexics, depending on the slight spectra energizing the eye, we cannot say which receptor field or relationship of receptor fields is controlling this movement from the existing experiment's data set—only that some relationship obviously exists for these dyslexic individuals that does not appear to exist in the vast majority of the "normal population."

FOCAL LENGTH

One of the major surprises of this experiment was that the focal length of the test subject's eyes varied markedly, depending on what composition of the spectral energy was presented to him. This phenomenon was previously unrecorded in the literature and was not expected. The other fact that surprised us in relation to this phenomenon was the magnitude of the focal length change, which in total was some 4.9 inches, varying from 12.3 to 17.2 inches. This degree of variation cannot really be accounted for by any known optical characteristic of the eye. As a result of this, the focal length variation was considered of particular interest.

When focal length was analyzed by the Receptor Field Energy Method, a number of interesting and unexpected things emerged. The first of these has already been noted, that is, that the three dominance groups exhibited a different gross performance variation. While the three dominance groups do, as in other cases, act as coherent groups obeying their own rules, there are marked differences in the way the three groups perform in relation to focal length.

The first and most obvious difference is in the performance of the N domain group, which only increases in focal length. In fact, if one looks at the data, one finds that one-third of the total variation in focal length is unique to this group, and it is all on the high (plus) side. If one looks at the general correlation chart (Table 9), one sees that the N domain only has a reasonable correlation in the $\mathcal{R}$-$\mathcal{G}$ and $\mathcal{B}$-$\mathcal{R}$ receptor field energy plots. (The energy levels are too close to zero in the $\mathcal{B}$-$\mathcal{G}$ and $\mathcal{B}$-$\mathcal{Y}$ fields for much cause and effect to be shown (Figures 56 and 57)). If one looks at the $\mathcal{R}$-$\mathcal{G}$ receptor field energy plot (Figure 58), one finds that the N domain points generally increase as the $\mathcal{R}$-$\mathcal{G}$ positive energy level increases, while in the $\mathcal{B}$-$\mathcal{R}$ receptor plot (Figure 59) they increase as the negative energy level increases. While the correlations are a little rough, [23] the general trend is there. The fundamental finding from this is that the focal length of the N domain gets worse as the field energy of red-related receptor field moves away from zero.

If one looks at Z dominant domain points on the focal length receptor field energy plots, one finds that the Z domain points form a reasonable correlation line in all the $\mathcal{B}$-based plots, as evidenced by the reasonable correlation factors for these items in Table 9. (This is in marked contrast to the reading speed plots where the Z dominant domain data appear to be random noise in these plots.) It would appear from these plots that focal length increases in these plots as energy becomes less positive and that it ranges both positive and negative.

While in the $\mathcal{R}$-$\mathcal{G}$ focal length receptor field energy plot, one finds that the Z domain energy level and focal length relationship is so parallel to the $\mathcal{R}$-$\mathcal{G}$=0 axis as to render any correlation questionable.

[23] This roughness is actually attributable to a single data point, which is one of those suspected of being a subgroup represented by a single data point. Is it also a poor data point in that as noted in the test data sheet as being almost too dark for the test subject to read.

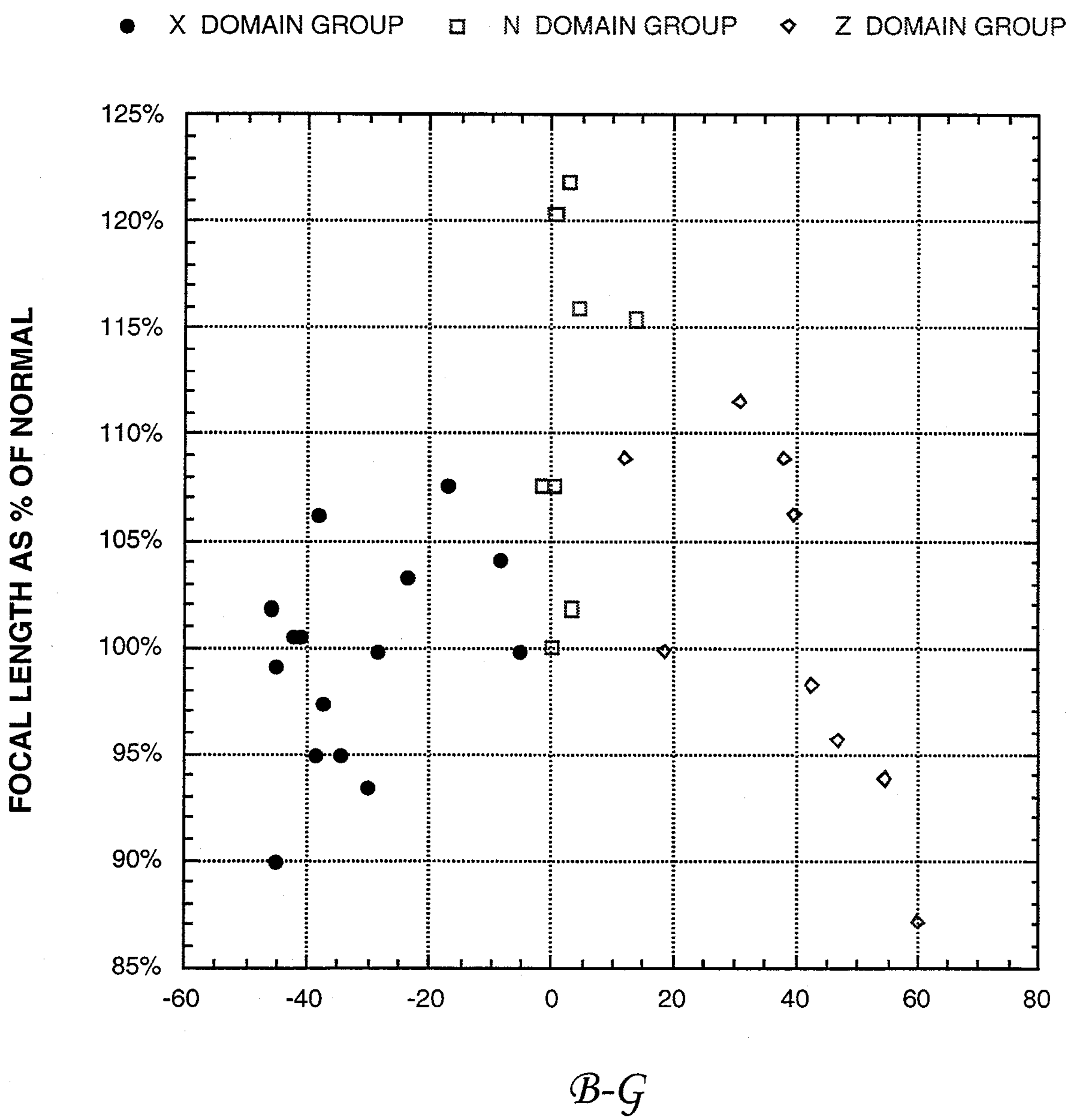

FIGURE 56. Rationalized ℬ-𝒢 Receptor Field Energy vs. Focal Length.

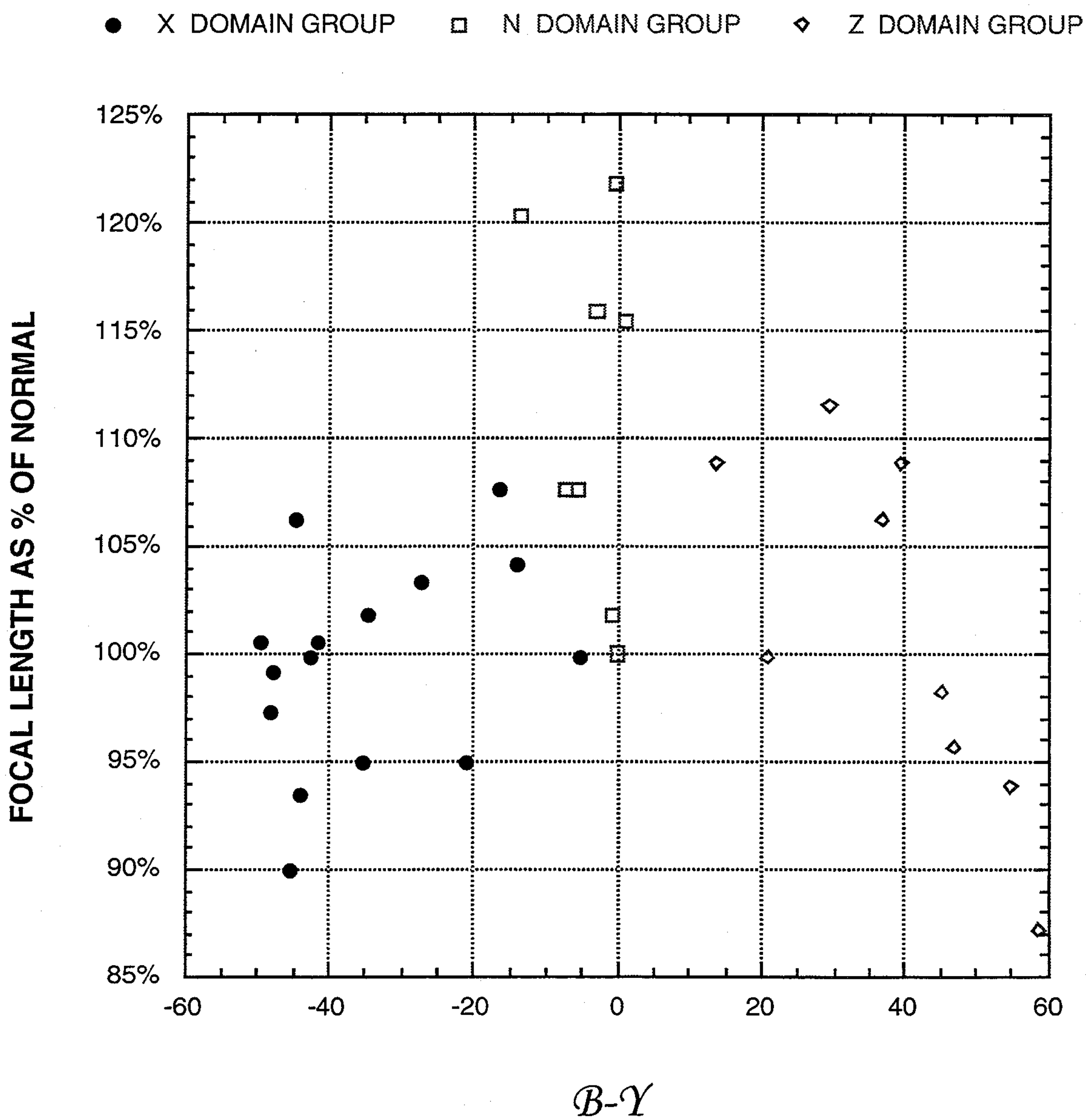

FIGURE 57. Rationalized ℬ-𝒴 Receptor Field Energy vs. Focal Length.

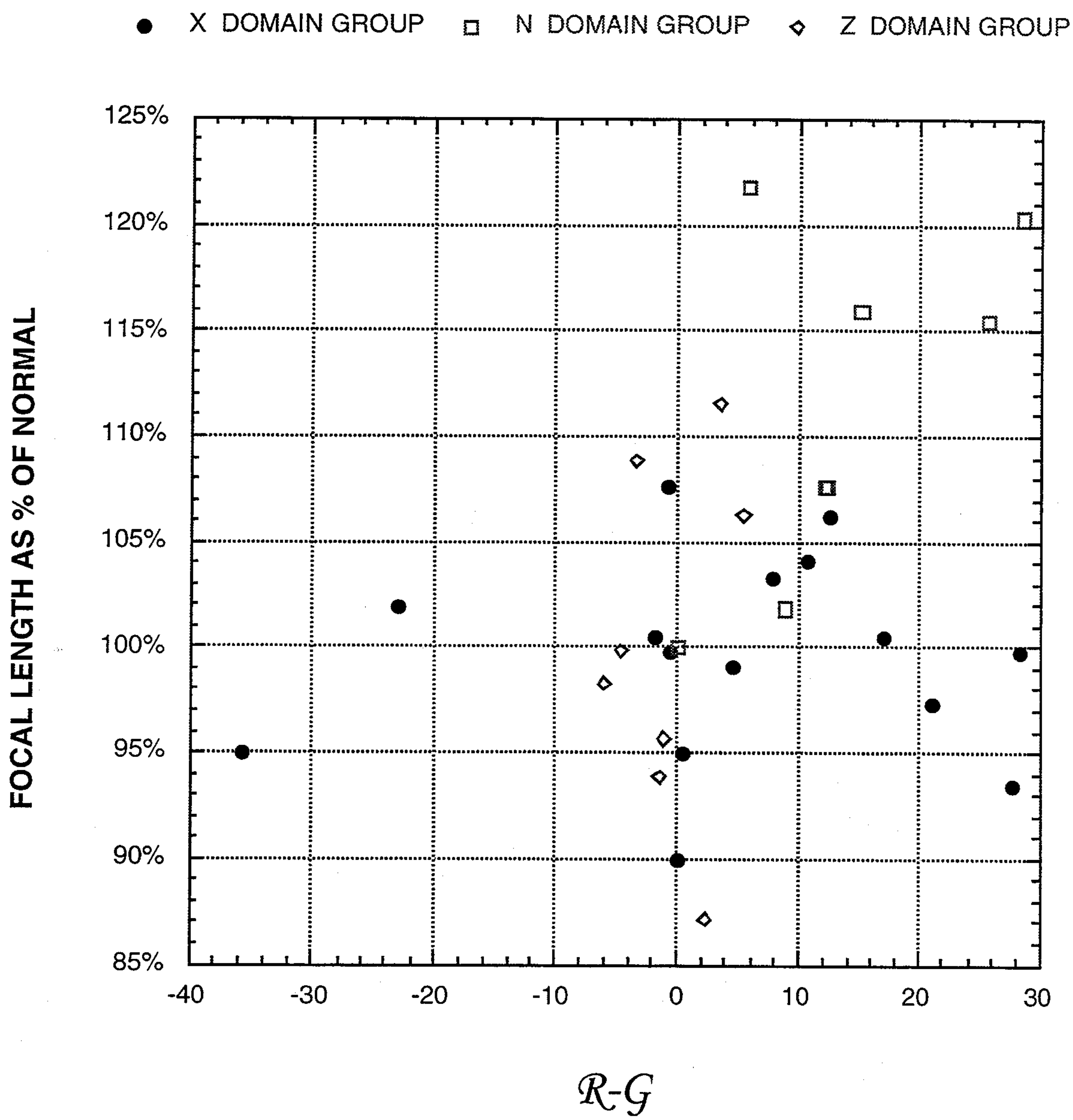

FIGURE 58. Rationalized R-G Receptor Field Energy vs. Focal Length.

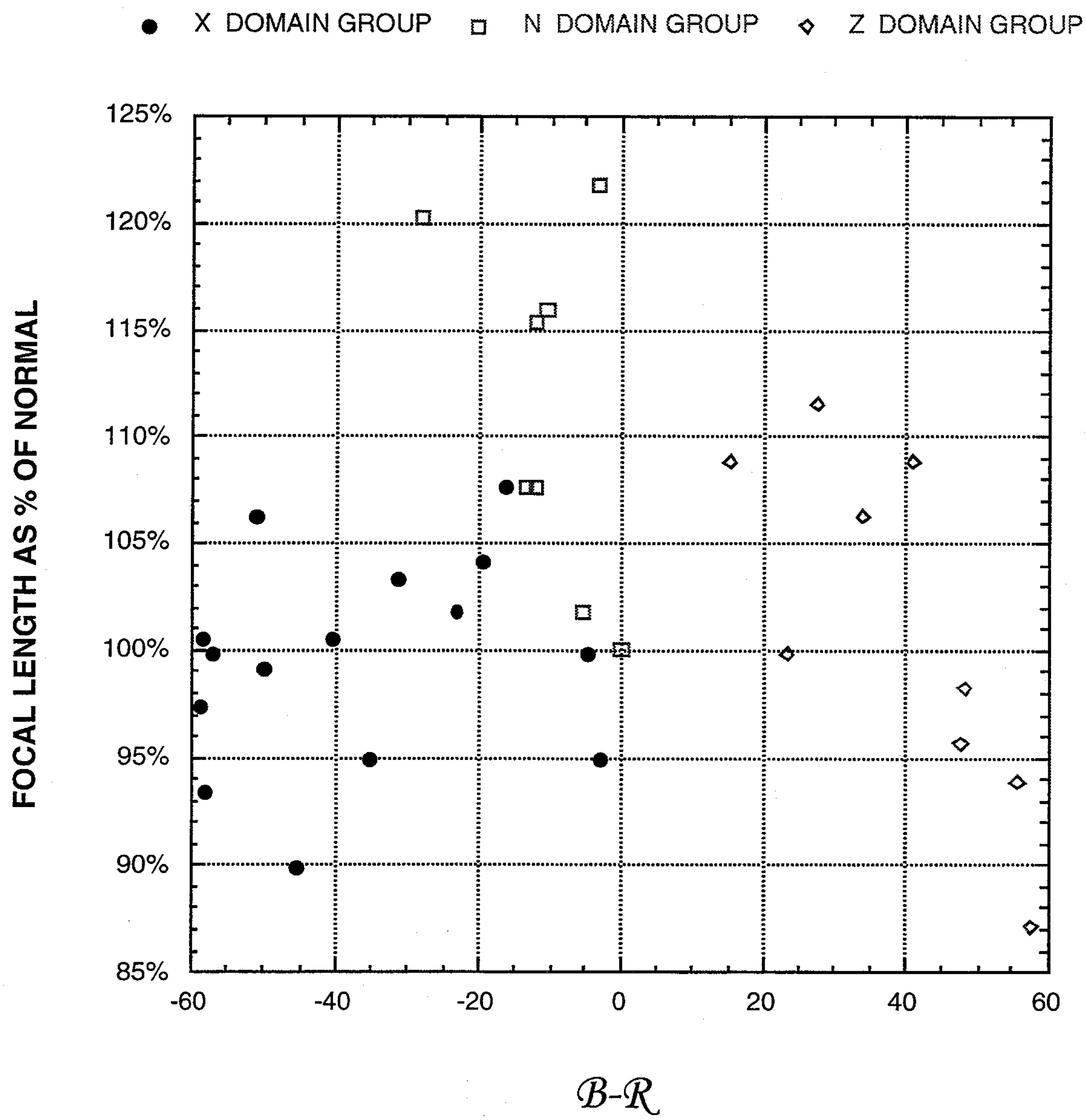

FIGURE 59. Rationalized ℬ-ℛ Receptor Field Energy vs. Focal Length.

By far the most interesting, and indeed surprising, find has to do with the X-dominant domain group. If one looks at the general correlation chart in Table 9, one finds that the correlation factors for the $\mathcal{B}$ related receptor field energy plots are only 0.39, 0.21, and 0.32 (very low), particularly when compared to the high-correlation factors seen for these points in the reading speed and angle of eye span plots. The reason for this lack of correlation is also fascinating, for if one looks at the $\mathcal{B}$-$\mathcal{G}$ receptor field energy plot for focal length, one finds that the last two points of our normally advancing curve as we approach $\mathcal{B}$-$\mathcal{G}$=0 from the negative side have bent over and are heading back down to the normal focal length level. There are three things worth noting about this:

1. That it happens, period.

2. That these two points continue to improve in both angle of eye span and reading speed even as the focal length moves back toward normal. (This downturn is evident throughout the other focal length plots.)

3. Where it happens, $\mathcal{B}$-$\mathcal{G}\approx$17 or 18 (this is important because a couple of the subjective factors discussed subsequently appear to bend over at this same energy level).

READING SPEED VERSUS FOCAL LENGTH

The previously noted return to normal focal length is of paramount interest because of this relationship to reading speed. If one looks at the relationship between reading speed and focal length, one finds that the highest reading speed occurs at the point where focal length has returned to normal for the X-domain group $\mathcal{B}$-$\mathcal{G}$ receptor field plot. (It is worth noting that this point (804) also has the closest-to-zero energy level in both the $\mathcal{B}$-$\mathcal{G}$ and $\mathcal{R}$-$\mathcal{G}$ receptor fields.)

This bend back is visible in all the focal length $\mathcal{B}$ energy plots, Figures 56, 57, and 59. An attempt to show a correlation for the two is shown in Figure 60.

Generally in the N domain, focal length and reading speed both get worse (Figure 61). In the Z-dominant domain, no relationship seems to exist between focal length and reading speed (Figure 61).

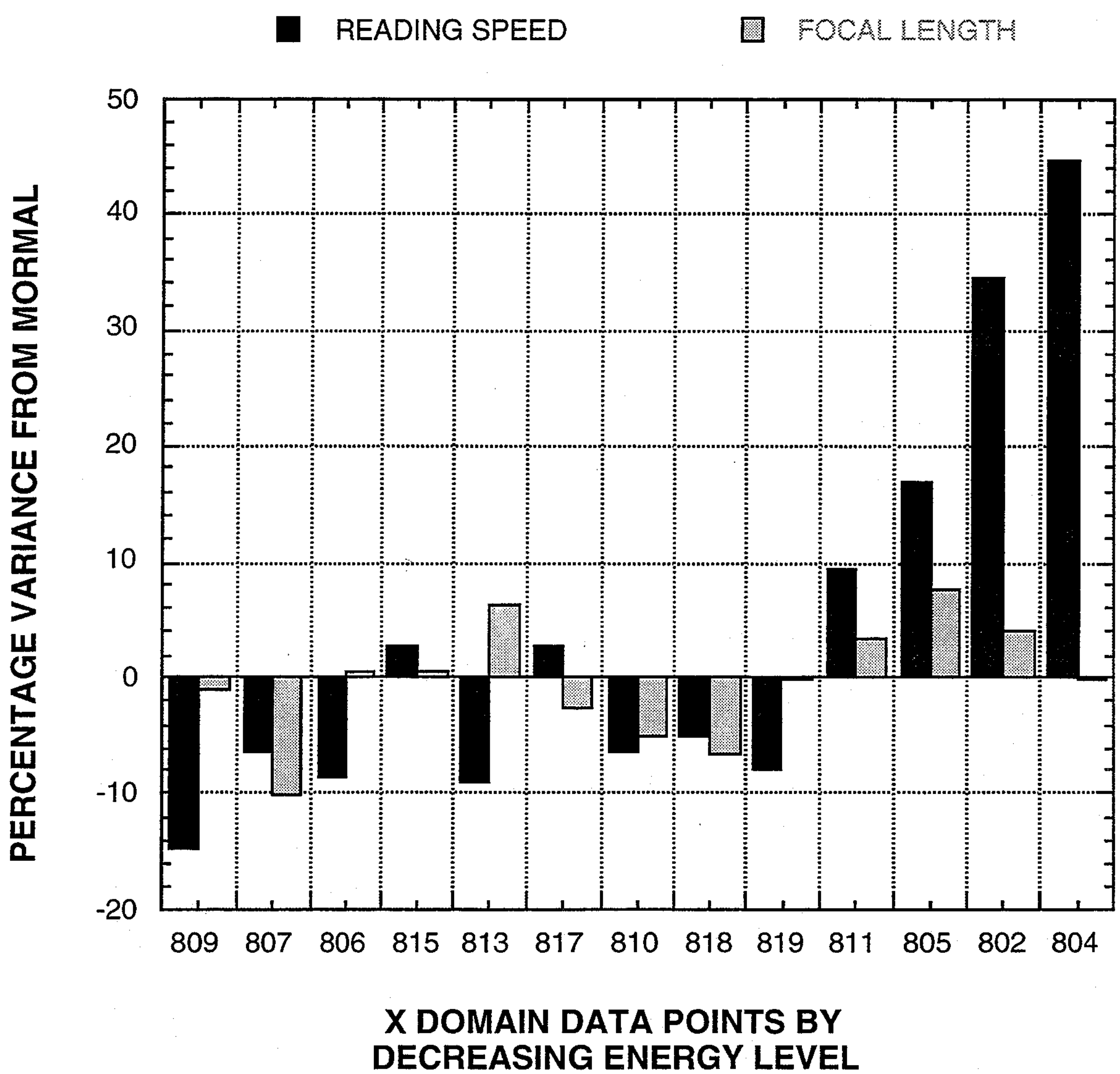

FIGURE 60. Interrelationship of Reading Speed and Focal Length.

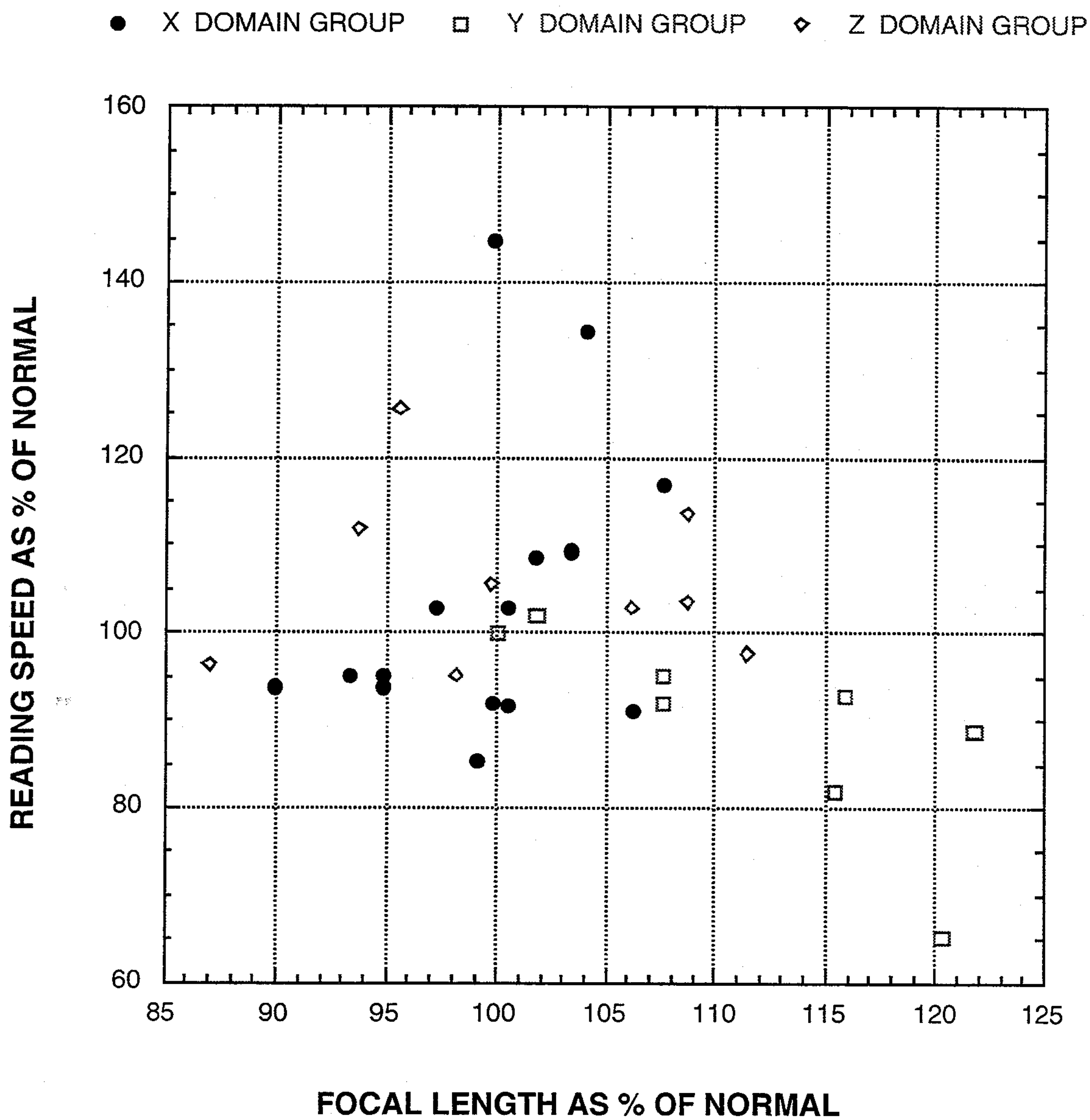

FIGURE 61. Interrelationship of Reading Speed and Focal Length by Domain Group.

ANGLE OF EYE SPAN VERSUS FOCAL LENGTH

If one looks at the angle of eye span versus focal length relationship (shown in Figure 62), one finds that generally the following apply:

1. For the N domain, as the focal length goes up, the angle of eye span goes down.

2. For the Z domain, the variation is so great and the subgroup problem is so severe that no real relationship can be justified. But it is interesting to note greatest angle of eye span occurs at a focal length equal to normal point.

3. For the X-dominant domain, there is a general rise in the angle of eye span with focal length, but at some point around an energy level of $\mathcal{B}$-$\mathcal{G}\approx 17$ this relationship breaks down. The relationship folds back on itself, and the focal length starts to go down, while the angle of eye span continues to rise. With maximum angle of eye span occurring at a point where focal length equals normal, this is also the point of highest reading speed.

This set of relationships is shown in Figure 63.

INTERRELATIONSHIP OF READING SPEED, ANGLE OF EYE SPAN, FOCAL LENGTH, AND ENERGY LEVELS

Some interrelationship obviously exists between (1) reading speed, (2) angle of eye span, (3) focal length, and (4) receptor field energy levels.

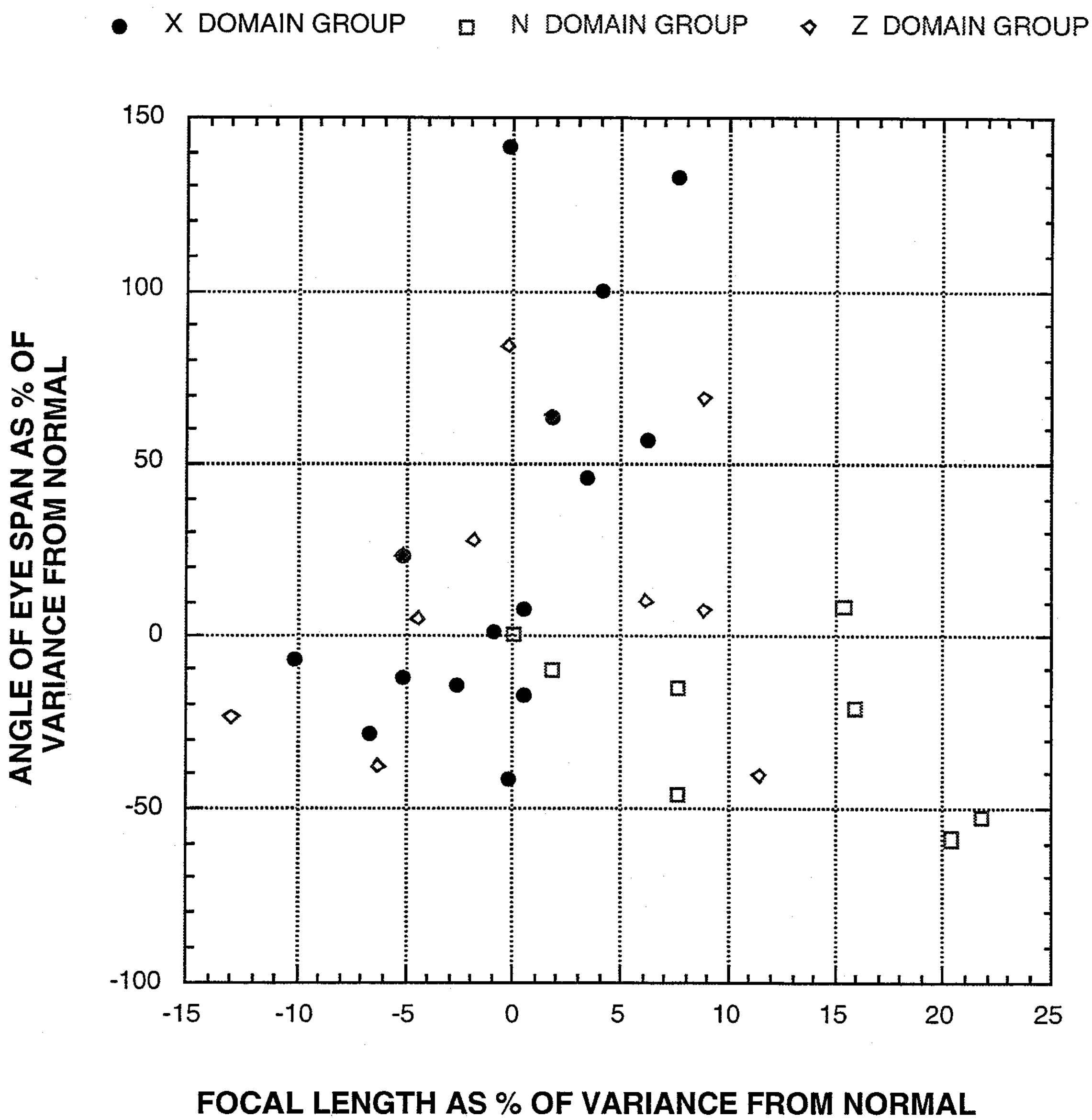

FIGURE 62. Angle of Eye Span Variance vs. Focal Length Variance.

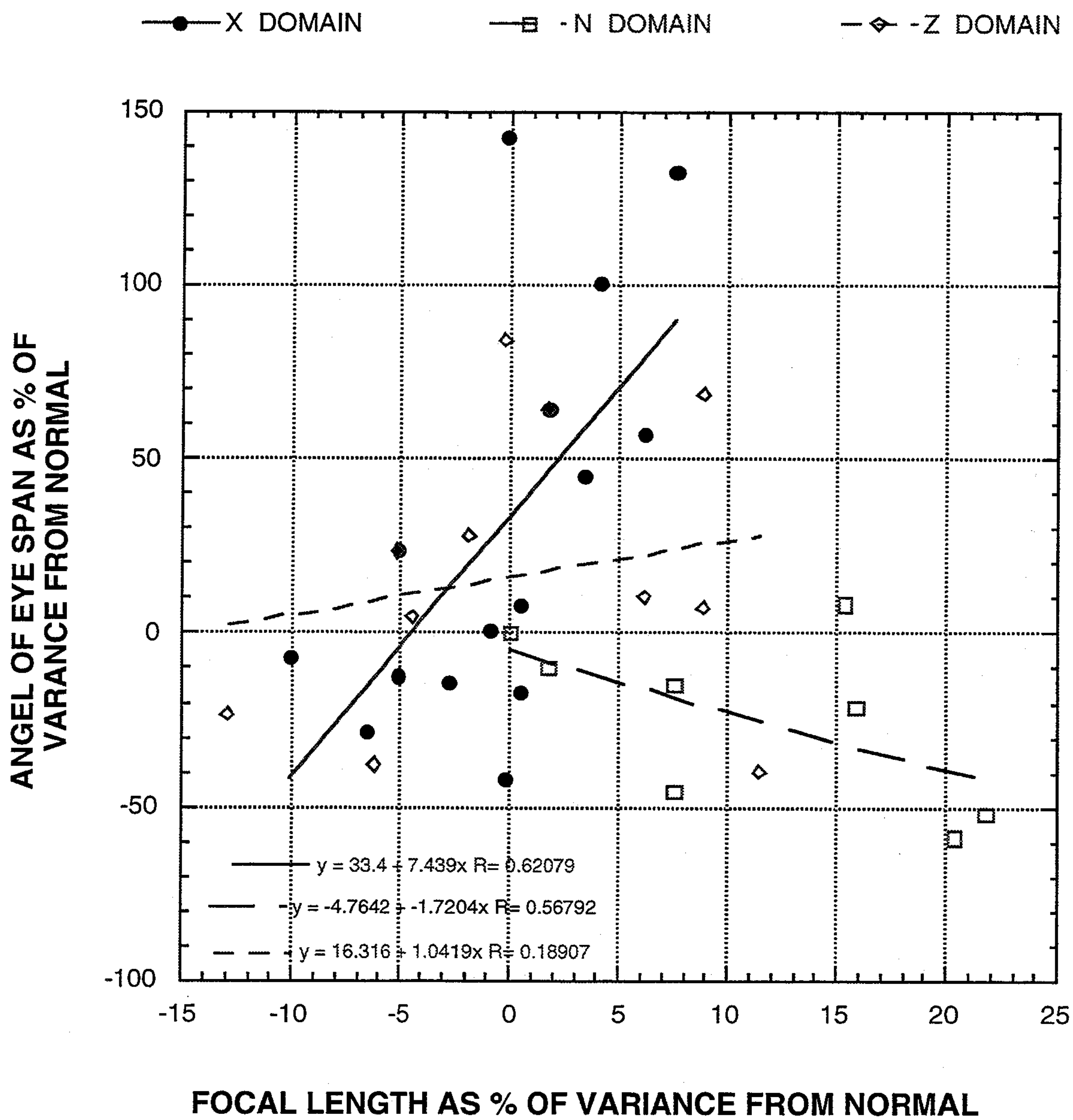

FIGURE 63. Angle of Eye Span vs. Focal Length Variant Diagram.

While it is reasonably obvious that the reading speed is probably a dependent variable that results from some relationship between angle of eye span and focal length, and while a three-dimensional plot of these variables does show that some general relationship exists (Figure 64), it appears that this relationship is more complex than a straight linear one. Whether this apparent complexity arises from one of the following conditions is unknown. [24]

1. Simple variation in the experimental data
2. The influence of some unknown and unaccounted for factor (an option that the author feels quite likely)
3. Insufficient data to arrive at an adequate understanding of the complexity of the interrelationship between the variables
4. Some relationship we have not found among the variables

What we can say about the relationship among the various factors is that

1. The domain dominant groups hold together and perform in a distinct interrelated manner unique to themselves for all three parameters (reading speed, angle of eye span, and focal length).

2. The three performance parameters are directly related to each other.

   a. Reading speed generally goes up as the angle of eye span increases.

   b. The angle of eye span is greatest when two conditions exist: the focal length is at or approaches its nominal value and the energy level in the controlling receptor field is low.

   c. The best reading speed generally occurs when there is maximum eye span at a nominal focal length.

The performance factors appear to be controlled by a given dominance group so long as the spectral energy received by the eye remains in that group's range. It would appear that under these spectral energy conditions, some given receptor field is paramount in controlling the various performance factors with different receptor fields controlling the vision system in different energy domains.

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[24] This is not for want of trying. A whole series of multiple variable regression, statistical analyses, test equations, pattern analyses, and variable movement studies failed to render a simple straightforward relationship between the various factors, which had a reasonable relationship to the totality of the data and had a reasonable set of confidence limits.

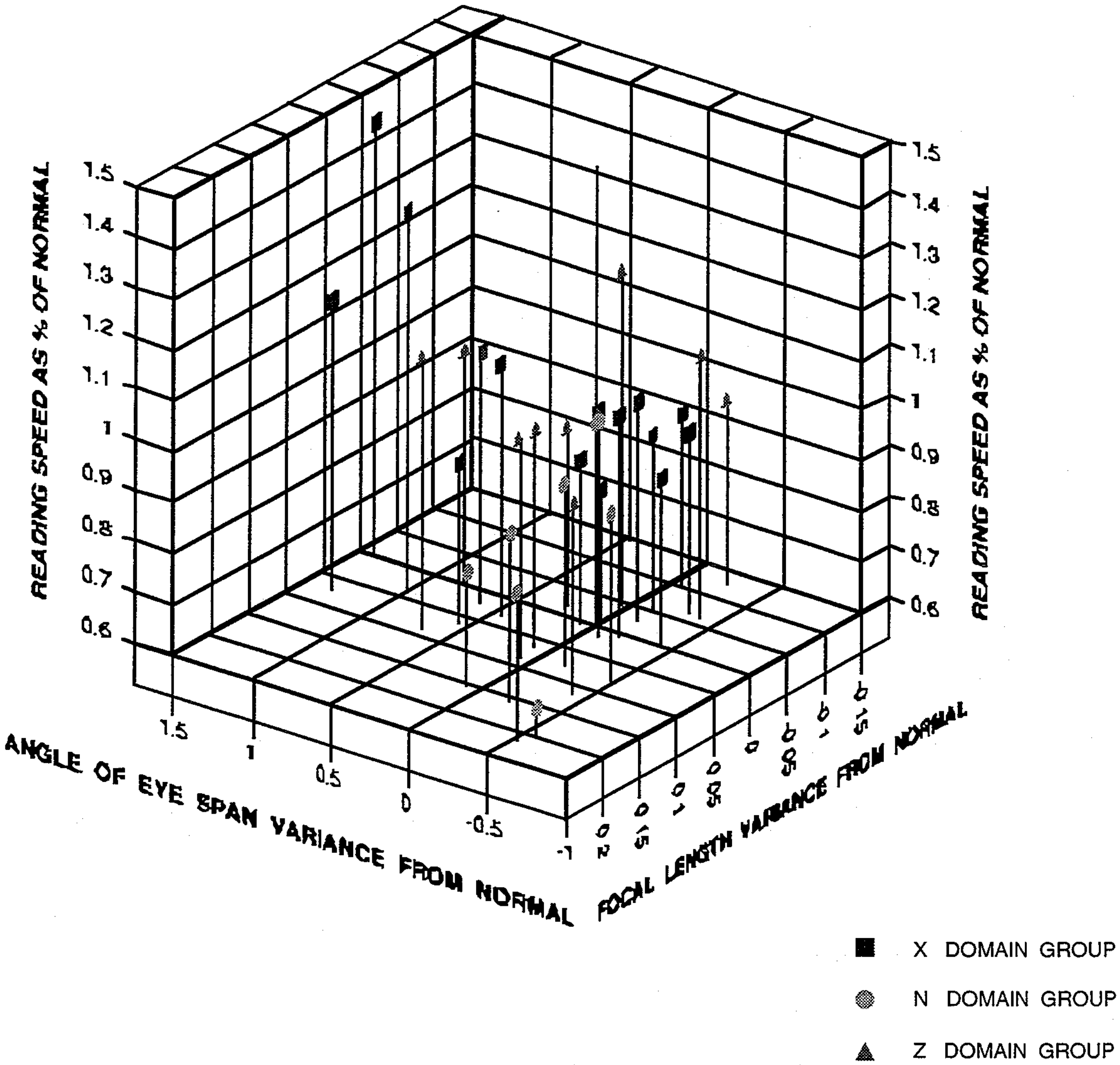

FIGURE 64. Performance Factor Variance.

Two other general observations can be made:

1. A performance factor in a given domain appears generally to improve as the energy of its controlling receptor field approaches "zero," but does not pass over it.

2. A relationship apparently does not exist between the performance of any factor for data point on the positive and negative side of zero in any receptor field. The two sides of the receptor field plot appear to act entirely different by depending on whether the energy balance is positive or negative.

REASONS FOR DOMINANCE GROUPING AND EFFECT

One of the main findings of this study is that dominance is a major causal factor in explaining visual performance in individuals with this type of dyslexia. This being the case, one is compelled to ask (1) what causes the filters to gather themselves into dominance groups and (2) why does such dominance grouping affect the visual performance of these individuals?

In answer to the first question, we find ourselves in the embarrassing position of fundamentally knowing the answer but being unable to state it precisely because of a lack of sufficient precision in the data set.

In the mid-1950s, Hurvich and Jameson [25] investigated the performance of color vision using the Hue Theory of Color Vision. In deriving their equation set, they found that their equations entered a zone of instability in the zone ranging from 475 λ to 498 λ (centered at about 486 λ) and from 536 λ to 520 λ (centered at about 578 λ). They were able through the use of higher-level mathematics to derive a set of equations to account for this, which is today widely used as the base of the hue or opponent color theory of color vision. They then went on to apply this mathematical method to determine the shift in Rayleigh spectral test results evaluation of abnormal color vision. [26] This was done by charting the movement peaks on these zones of instability. Their method is today one of the major advanced techniques of evaluating and quantifying abnormal color vision and can be found in all major text books that discuss color vision problems. (From our point of view, one is probably better off thinking of this mid-point as an asymptotic boundary to a dominance domain.)

Our problem is in applying this knowledge of the existence of this asymptotic boundary of dominance domains to our existing data set. These problems can be described as follows:

1. While some tests make it possible to determine the location of these asymptotes very precisely for a given individual, we did not run them. In fact, starting out this experiment had no reason to consider that performing these tests would be of great significance. [27]

[25] Hurvich and Jameson, 1955 to 1956.
[26] Jameson and Hurvich, December 1956.
[27] Actually, it was considered and rejected on the basis of equipment availability and irrelevancy of the data to what we were doing—hindsight is such a great clarifier of experimental design.

2. If one looks at the published data, one finds that this asymptotic domain boundary is really a region of ±12 or ±15 λ for normal individuals for both of them. If one includes the normal types of color vision abnormalities, this tolerance zone increases to about ±25 λ. Furthermore, the mean of this tolerance zone (the meaningful parameter) shifts by ±6 λ for normal and more for the abnormals (where its shift occurs in definitive stages). Our problem is that this total variability represents a minimum of 12% of the statistical universe for normals and 35% for abnormals. It does not take a lot of higher-level statistical knowledge to know that, if your variability ranges from 12% to 35% of the statistical universe of what one is measuring, to have a meaningful mean with any degree of confidence, one is going to need a wheelbarrow full of data. We do not have quantity of data and much of what we do have is in the wrong place to use for making intuitive judgments.

3. Furthermore, we know through the work of Nathans [28] that normal variation of the R-G asymptote (one of the most interesting to use here) is caused by a series of genetic variations of the dye in the green cone and in reality repeats a series of real and discrete variations as opposed to a statistical variation (as presented in most of the older literature).

4. The other problem is that Hurvich and Jameson did their research in an era before the development of Reflector Field theory, when people believed that the cones inputted directly into the brain. As a result, almost all discussion of the phenomenon is based on a direct color input frequency model as opposed to the phenomenon working in an energy balance reflector field system. [29] If one tries to convert these data into reflector field energy balances, one runs into the variability problem again and finds that the probability zone of occurrence covers about half the potential data set.

The result of this is that while one can safely conclude that the asymptotic boundary we are seeing in our data is the same one that has been observed and reported on in the literature for half a century. Furthermore, the existing literature on color vision and color vision abnormalities says such an asymptotic boundary should occur in "about" the places we are seeing them. Because of the limitation of our data set and the nature of the discussion of the phenomenon in the literature, we are unable to place these boundaries in the data field with any precision. However, the existence of the asymptotic domain boundaries is not a new or unexpected phenomenon and in fact has been known for half a century or longer.

[28] Nathans, p. 42-49.

[29] While such a discussion may exist in the literate (it did not jump out of our literature search on the subject).

What is new and unexpected (and previously unreported in the literature) is the fact that crossing over one of the asymptotic domain boundaries should cause massive changes in vision performance in the form of changes in focal length, angle of eye span, and reading speed in 10% to 15% of the population with dyslexia (or at least some portion thereof). While the real reason for this phenomenon at a physiological level is beyond the scope of this paper, one can hypothesize that it is caused by

1. Some interaction in the retina of the eye.

2. The result of modulating timing signals from the receptor fields to the visual processing center of the brain (currently a very popular subject among dyslexia theories).

3. Some abnormality in the receptor field and cone dye constituents (the historical favorite).

What this study's data show is that this shift does occur in some (or all) dyslexics suffering Irlen's Scotopic Sensitivity Syndrome. The study also shows that this phenomenon is measurable and quantifiable, using the methods described in this study, and has a significant impact on the visual performance of individuals having this problem.

Based on this study, a reasonable hypothesis is that this shift in performances does not occur in the bulk of the "normal" population and is one of the things that separates Irlen-type dyslexics from the normal population in visual properties. This supposition is not based on the findings of this study, but on the lack of the previous reporting of this phenomenon in the literature. If it were a general phenomenon affecting the whole population, someone should have spotted it in the last half century and reported on it.

It is, however, possible to back into an understanding of asymptotic domain boundaries as it affects this experiment by application of the general theory of human vision. This takes some rather extensive explanation of the background theory. Since this explanation is pertinent to the understanding of one of the main findings of this study, it is probably a worthwhile endeavor.

HISTORIC BACKGROUND OF COLOR NULL ASYMPTOTE THEORY

Color vision defects have been known and studied for years. As a result, vast literature on them is available, and methods to study them have been worked out. The standard test for studying classic color vision defects is the Rayleigh Color Matching Test, which locates color vision shifts in people's vision by matching a composite color against a known standard color. This test

was developed by Lord Rayleigh in 1881 and has been in use for over 100 years. The shifting measured by this test is normally explained in classic three-cone color theory as the shifting of the points of intersection of the three-color frequency response curves.

The points are described as points of balance between the cone excitation energy where it is possible to measure its shift. This is the standard method of determining the type of color blindness an individual has, where the point is called the "zone of confusion" (see the following discussion).

The balance points used in this test are known with great precision, with a lot of experimental work having been done to identify these points of balance accurately for the "normal population." The presently accepted international standard for these points was worked out by W. D. Wright in the 1920s and is shown in Figure 65.

Hurvich and Jameson did extensive work on abnormal color vision using the Opponent Color Theory of Color Vision (in 1956). This study of abnormal color vision has become famous and is now summarized in some form in all major text books on color vision. While most of this experimental pioneering work in abnormal color vision does not concern us here, one derivative of it does. Based on their findings, Hurvich and Jameson developed a new theory of human color vision, which became known as the Hue Opponent Color Theory (referred to previously). In this system, there are three channels that carry color vision information to the brain. This system is normally shown schematically in many modern texts with the black and white being made up of some combination of cone energies. This is not actually in accordance with Hurvich and Jameson's original model, which is shown in Figure 66.

This Hurvich-Jameson system was one of the major theories of human color vision for 40 years (before the development of the modern Receptor Field Theory) and is discussed at length in all older text books on color vision. Again, a detailed discussion of this theory is beyond the scope and needs of this paper.

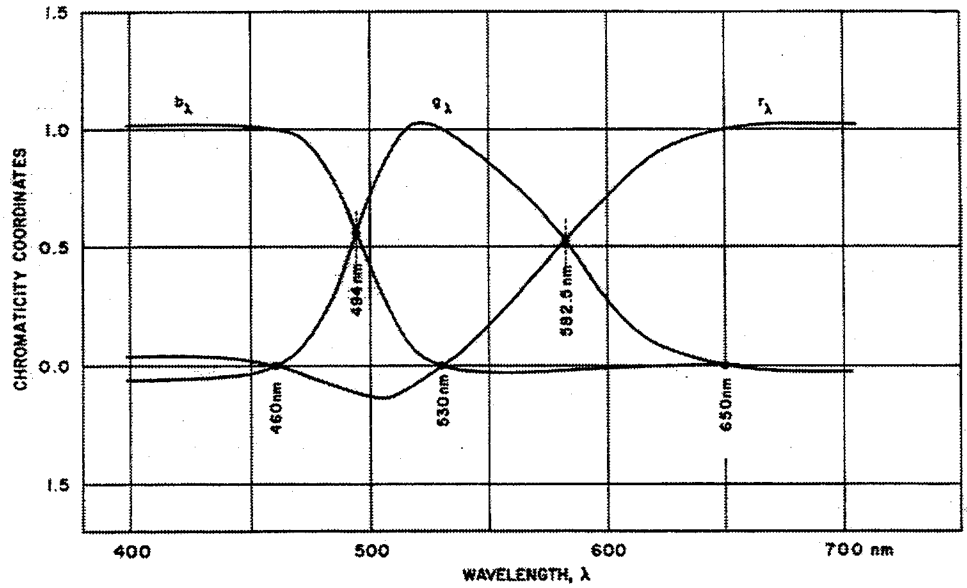

FIGURE 65. Wright's Mean Color-Matching Chromaticity Points for the Normal Population.

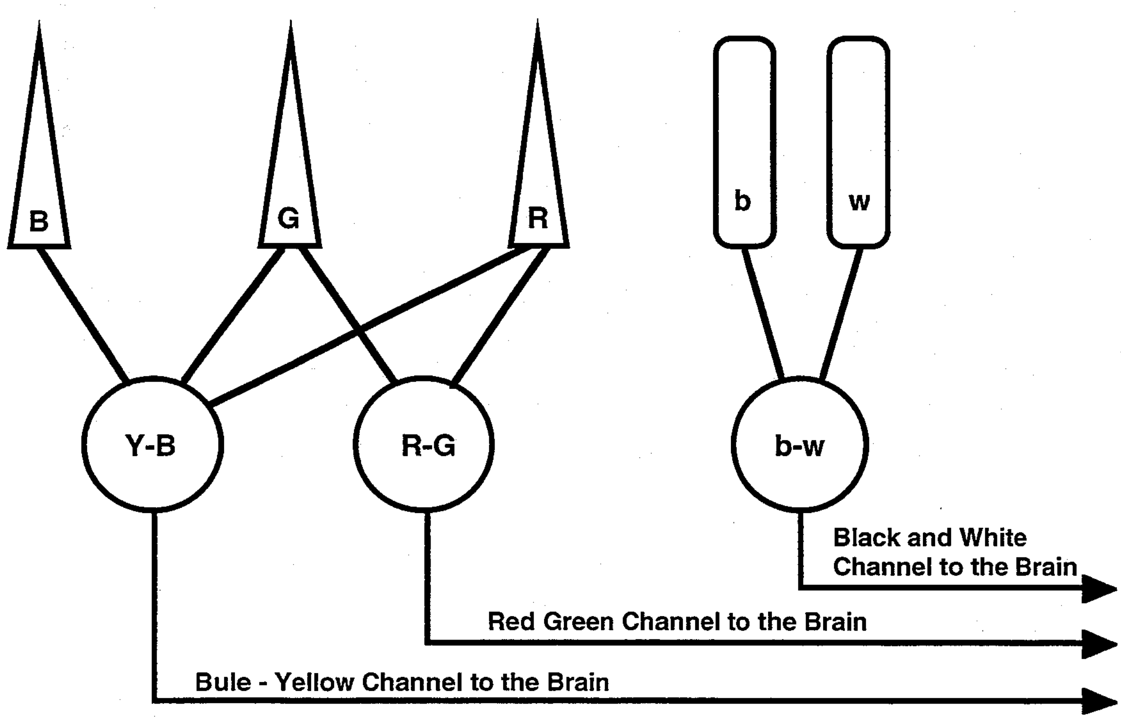

FIGURE 66. Schematic Diagram of Hurvich and Jameson Channel Theory.

What is important to use here is the explanation of the null point asymptotes revealed as a result of the Hurvich and Jameson theory. The equal energy balance points of the classical theory were extended to be null signals in the R-G and B-Y color channels in their theory. These, in turn represented equal null energy asymptotes running through color space. This arrangement is normally represented in most text books on the standard C.I.E. color space diagram as shown in Figure 67.

In this diagram the R-G and B-Y lines represent balance (or null) energy through color space and in so doing divide color space into four sections. [30] The exact location of the "channel lines" and their end points tends to move somewhat depending on the "vision theory" and definition of whiteness being used. While a decision of the nuances of variation between them is beyond the scope of this report, one should be aware that differences do exist, dependent on the theory used. The basic idea represented by them is essentially the same and is what is important here.

NOTE ON WHITENESS

The Hurvich-Jameson system has in it a whiteness channel (white-black) essentially to determine raw-color signal strength. The reason for this in the Hurvich-Jameson system is summarized in a contemporary text book on color vision: "We've stressed that there are three attributes of any color and that there are three cones. Unless there is a third channel, your brain could be aware of only the two attributes of color represented by 'red-greenness' and 'yellow-blueness.' This third opponent channel—the white minus black channel (w - bk)—relays lightness information." [31] (A reasonable summary of Hurvich and Jameson more complex and lengthy explanation.)

In short, the Hurvich and Jameson system has two channels and three unknowns and, therefore, needs a third channel to make the math come out right. It must be pointed out that in the Receptor Field Theory of Color Vision, there are four fields or channels (16 if one counts the mirror-image contour sign equivalents embodied in some versions of the theory). This produces a four-equation three-unknown problem, which in theory the brain can solve and even has a spare check channel for, without the need of a w-b signal.

This fact not withstanding, such is the historic influence of the Hurvich-Jameson theory that many have hypothesized the existence of a black and white receptor field. [32]

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[30] Falk, Brill and Stork, p. 277.
[31] Falk, Brill and Stork, p. 276.
[32] Hubel, pp. 187-188.

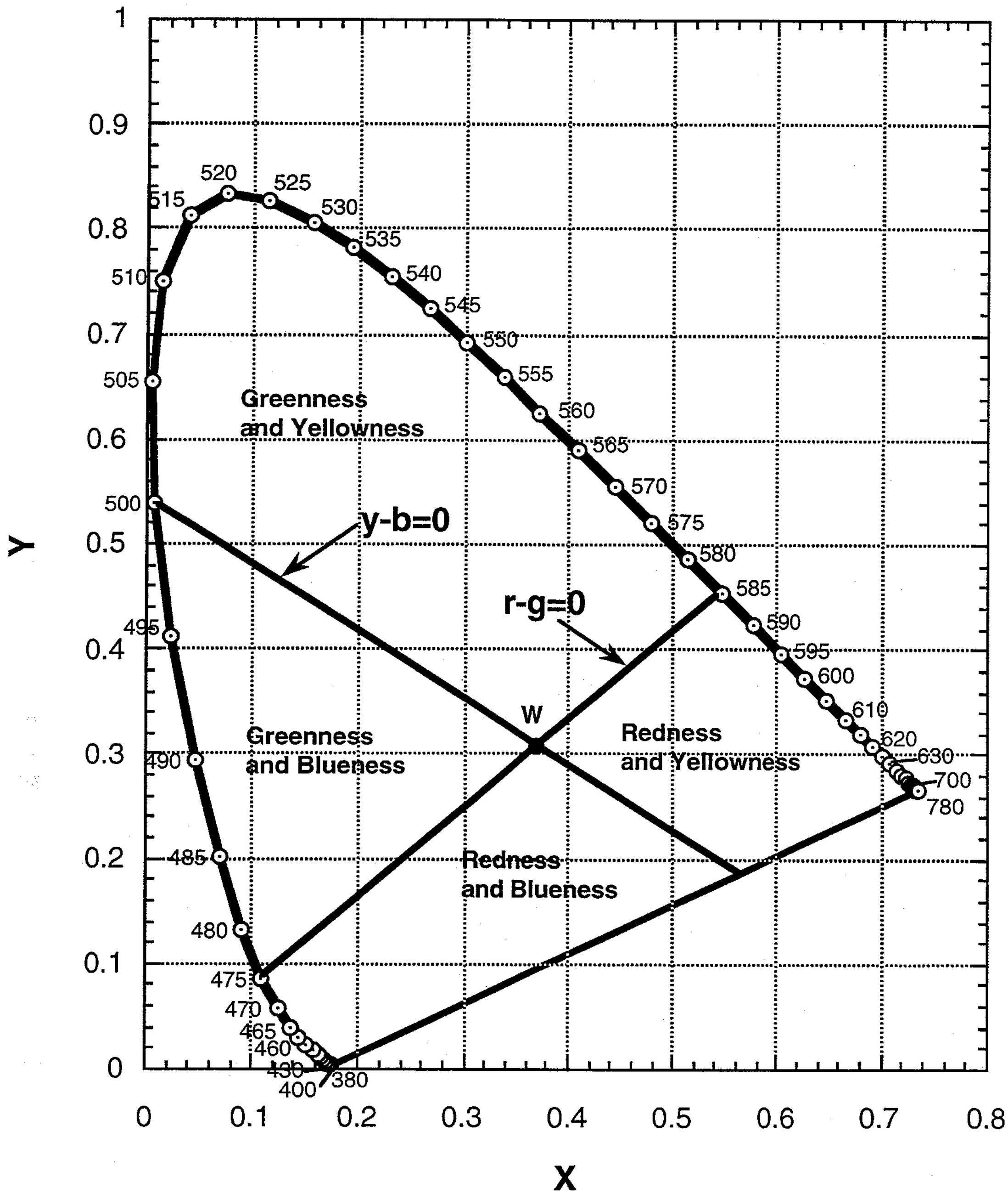

FIGURE 67. 1931 C.I.E. Chromaticity Diagram Showing Hurvich and Jameson Channel Theory.

As a result of the needs for a w-b channel in the Hurvich-Jameson system, a number of theories regarding the composition of "white" have been proposed. As part of this analysis, the list of proposed whites was run against the reading speed data with no correlation being found, which led the author to question the existence of a w-b receptor field, particularly since it is unnecessary in a Receptor Field Theory system to resolve the equation set.

RECEPTOR FIELD THEORY

Most of the text book discussion of the null asymptotes is done on the basis of wavelength of light within the framework of classic three-cone or hue theory, which presents something of a translation problem for us here. But if one believes in a Receptor Field Theory where color vision consists of R-G, B-R, B-G, and B-Y fields, one must ask what the null asymptotes mean in this context. Under this Receptor Field Theory, they would represent the null points where $\mathcal{R}=\mathcal{G}$ resulting in $\mathcal{R}-\mathcal{G}=0$, $\mathcal{B}=\mathcal{Y}$ resulting in $\mathcal{B}-\mathcal{Y}=0$, $\mathcal{B}=\mathcal{G}$ resulting in $\mathcal{B}-\mathcal{G}=0$, and $\mathcal{B}=\mathcal{R}$ resulting in $\mathcal{B}-\mathcal{R}=0$.

The problem is that under the Receptor Field system there are four fields—not just two—and one must ask where are the null asymptotes for the $\mathcal{B}-\mathcal{R}$ and $\mathcal{B}-\mathcal{G}$ fields in color space.

If one runs the energy calculations for the four fields and plots them on the standard C.I.E. diagram, one finds that they represent the $\mathcal{B}-\mathcal{G}=0$, $\mathcal{B}-\mathcal{R}=0$, $\mathcal{B}-\mathcal{Y}=0$, and $\mathcal{B}-\mathcal{G}=0$ lines of Figure 68.

If one graphs the data points and their domains on the standard C.I.E. chromaticity diagram (Figure 69) and then superimposes the four "zero"-point asymptotes of human vision on the same C.I.E. chromaticity diagram, one finds a remarkable correlation between the performance grouping of the data and bisecting null asymptotes as shown in Figure 70.

These asymptotic divisions correspond reasonably closely to the performance data in all cases, but the $\mathcal{R}-\mathcal{G}$ domain case, where there is apparent discrepancy in the location, requires some discussion.

The $\mathcal{R}-\mathcal{G}$ null asymptote is close but is in need of some adjustment to conform to the data. If one were to shift the $\mathcal{R}-\mathcal{G}$ asymptote up by about 1λ or rotate the $\mathcal{R}-\mathcal{G}$ asymptote about the optical center of vision by 1.5 to 2λ, one would find that one would get a near perfect fit with the experimental data as shown in Figure 71. The question that one must ask, however, is "is such an adjustment justified?" This unfortunately requires some protracted discussion of the concept of normality of human color vision and the historical development of C.I.E. Color Space Diagram, a discussion of which follows.

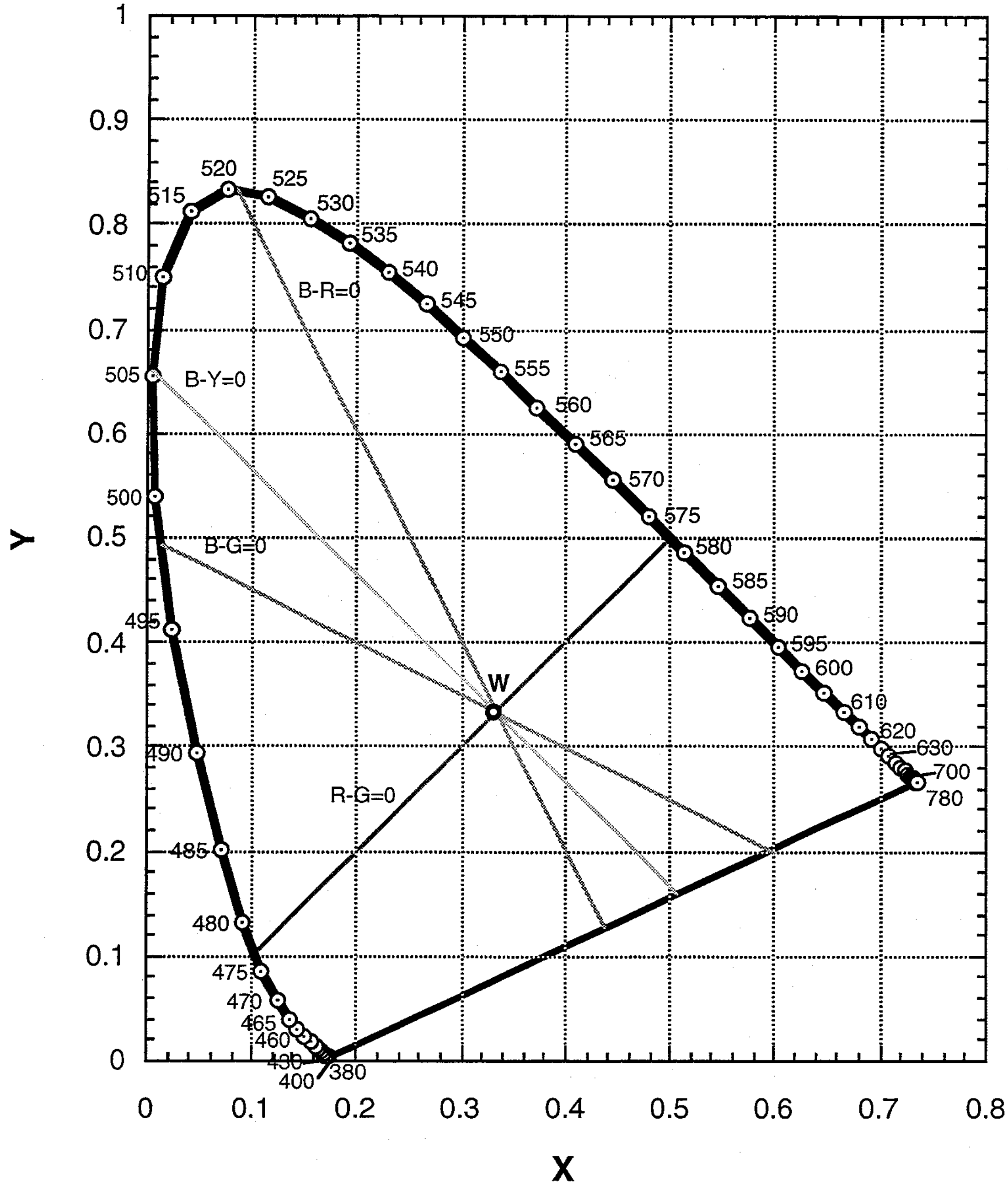

FIGURE 68. 1931 C.I.E. Chromaticity Diagram With Energy Receptor Field Null Asymptotes.

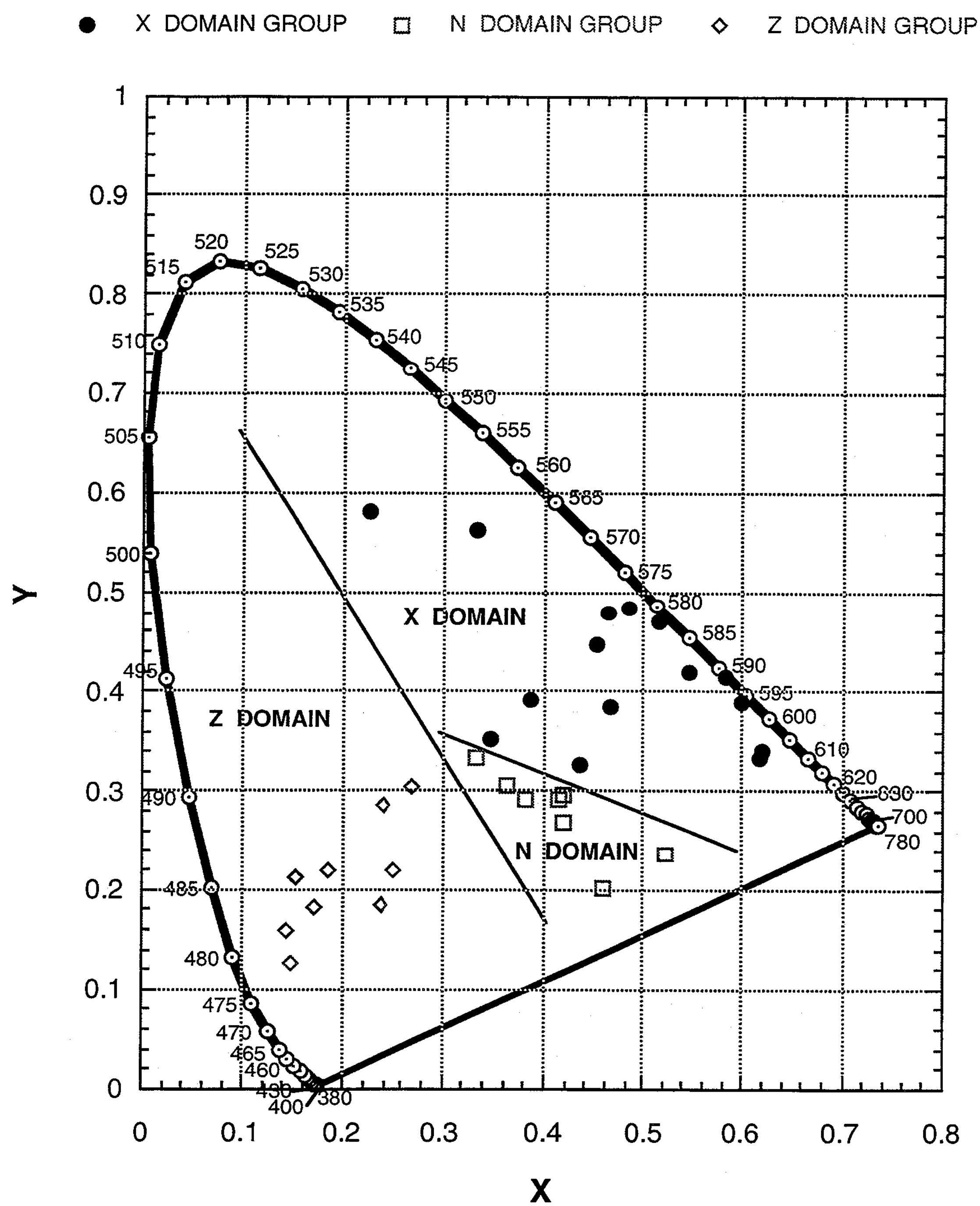

FIGURE 69. C.I.E. Chromaticity Diagram Showing Data Points and Domain Groupings.

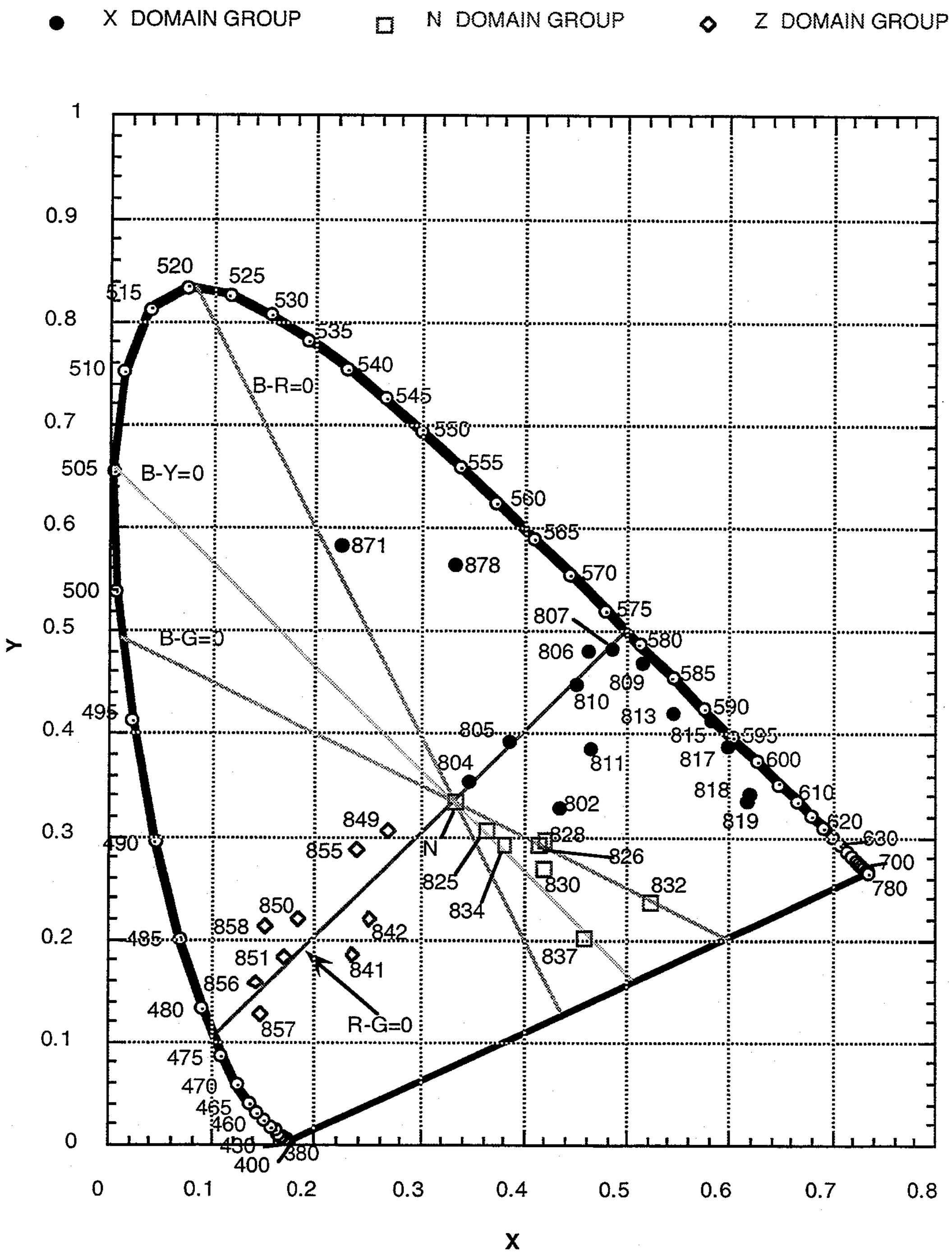

FIGURE 70. 1931 C.I.E. Chromaticity Diagram Showing Receptor Field Null Energy Asymptotes and Data Points.

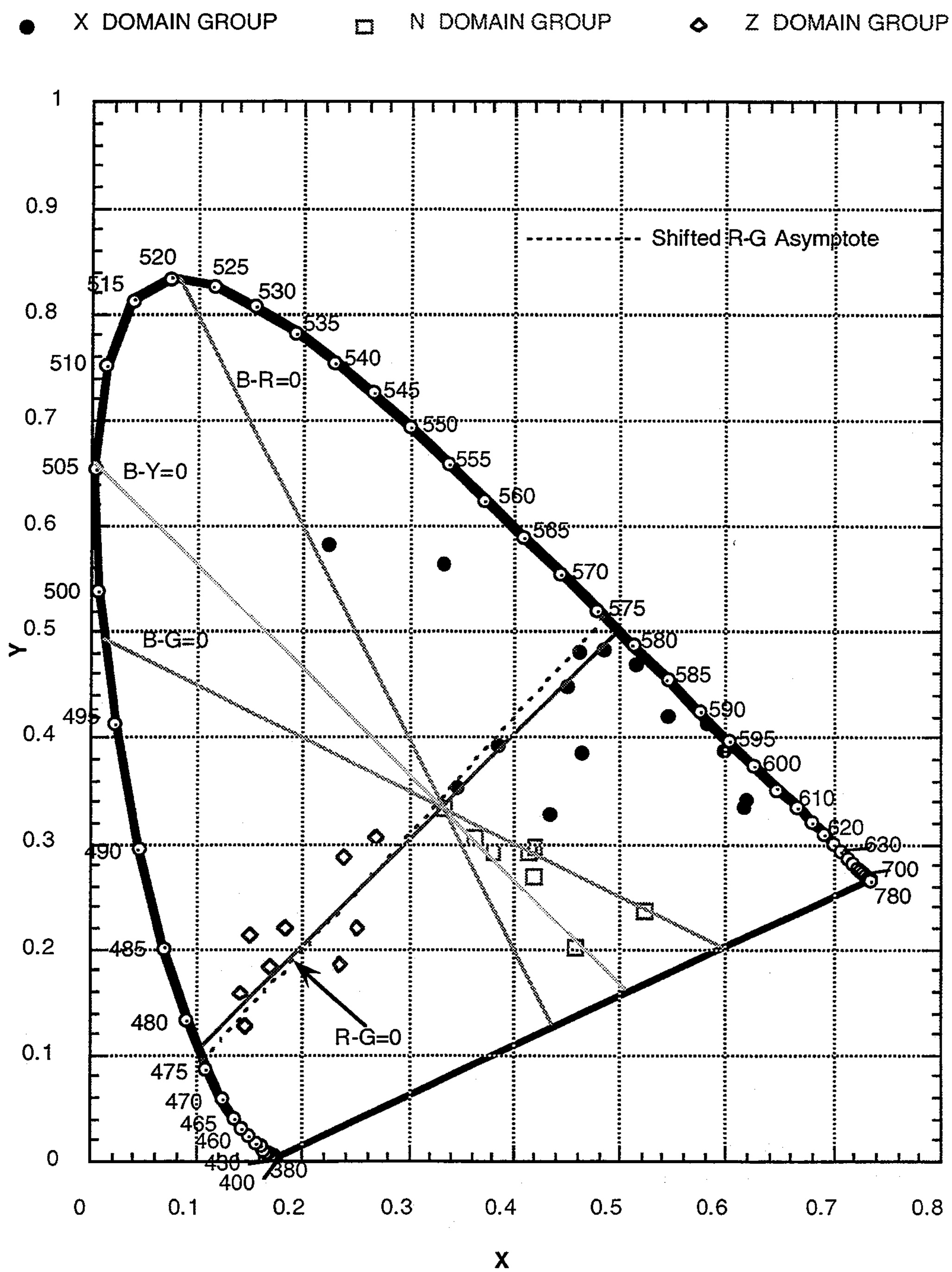

FIGURE 71. 1931 C.I.E. Chromaticity Diagram Showing Receptor Field Null Energy Asymptotes and Data Points.

DISCUSSION OF NORMALITY OF HUMAN COLOR VISION AND DEVELOPMENT HISTORY OF C.I.E. COLOR SPACE DIAGRAM

While a full technical discussion of the historical/vagaries of the C.I.E. Color Space Diagram is beyond the scope of this report, trying to portray the inner-locking three-component color system of the human eye on a two-dimensional diagram presents real technical difficulties. Before the C.I.E. standardization, about 60 systems were in use to depict human color vision. The C.I.E. went though all these proposed systems before selecting the current C.I.E. standard representation methodology. (For a discussion of these systems and why the C.I.E. adopted the one it did, see Le Grand Chapter 7.)

For discussion purposes, the C.I.E. is neither good nor bad—just accepted.[33] The C.I.E. Color Space Diagram is used here simply because it is the accepted standard.[34] The fact that it is not perfect is demonstrated by the fact that perhaps another 60 systems have been proposed in the literature since the adoption of the C.I.E. as the international standard in 1931. However, some explanation of its derivation and limitations is needed here and is germane to our data analysis.

The C.I.E. diagram was derived with an unusually tight tolerance set, much tighter than that used in the average definition of "normal human color vision." The C.I.E. is derived on the basis of what is known in mathematics as a modal average, in which those that derived the C.I.E. discarded from their database of "the normal color vision population" anyone who showed any "color vision abnormality." This "outlying population" turned out to be about 20% of the "normally normal" population. This was on top of the already known excluded "abnormal" (color blind) portion of the population (which represents 8.5% of the population.[35] Having cut the tails off its distribution, the C.I.E.'s developers then averaged this modal population, to come up with a diagram to represent this "average normal" population. The result is that this C.I.E. modal average diagram for the "normal population" is really much tighter than the real and accepted "normal population."

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[33] Though a couple of the less common representation systems appear to give an easier presentation of the results.
[34] Some of the more specialized systems may actually be better at depicting the dyslexic condition and its use here should not be considered an endorsement.
[35] Judd and Wyszecki, p. 71.

NORMAL COLOR VISION DEFINITION

The standard accepted variation in "normal" color vision is actually quite large, as can be seen in the standard text book diagram showing normal and abnormal color vision as derived by Judd in 1943 [36] (Figure 72).

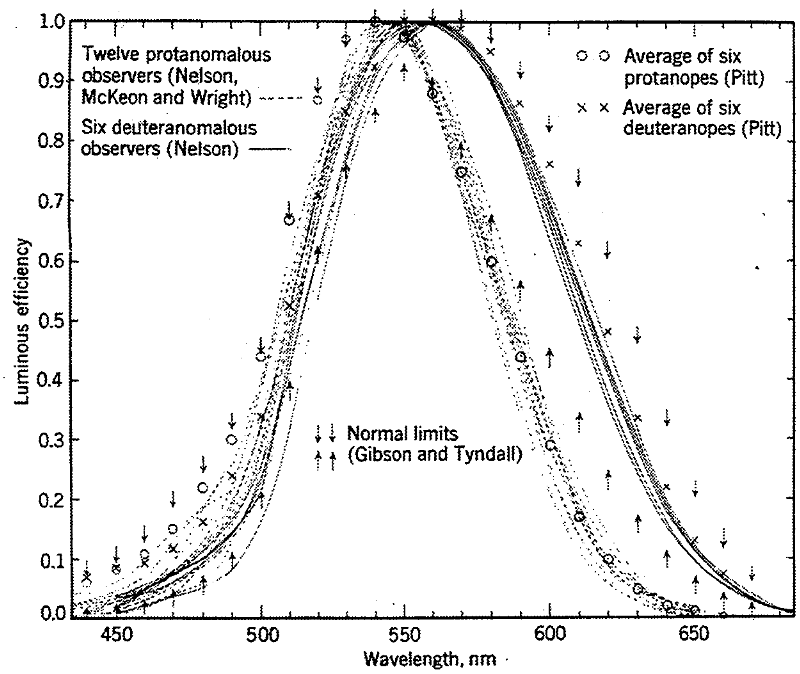

FIGURE 72. Standard Diagram of Visual Response of Normal and Abnormal Population.

The diagram in Figure 72 is traditionally used to discuss the difference between the abnormal color vision population, those with various forms of "color blindness", represented by the inner curve, and the "normal color vision" population, represented by the outer curve.

The shifts in the vision asymptotes caused by this "abnormal color vision" are well known and well studied. These are generally shown on the C.I.E. Color Space Diagram (Figure 73) in most text books, [37] where they are explained in classic three-cone color vision theory. These shifts are referred to as zone of confusion, because the observer's conal color vision system cannot distinguish between colors in a color-matching test. The subject's color vision is

[36] Graham, et al., p. 408.
[37] Graham, et al., p. 401.

therefore said to be "confused" in these zones. The zones are dependent on the nature of the color blindness. Two things are worth noting on this standard diagram:

1. The shifts in the vision asymptotes are recognized as zones rather than line asymptotes. This is because the extensive work done on abnormal color vision over the last five or six generations has shown that a reasonably wide statistical spread exists in the color perception threshold of the abnormal color vision population. (Zones roughly correspond to the tolerance range shown for abnormal color vision in Figure 72.)

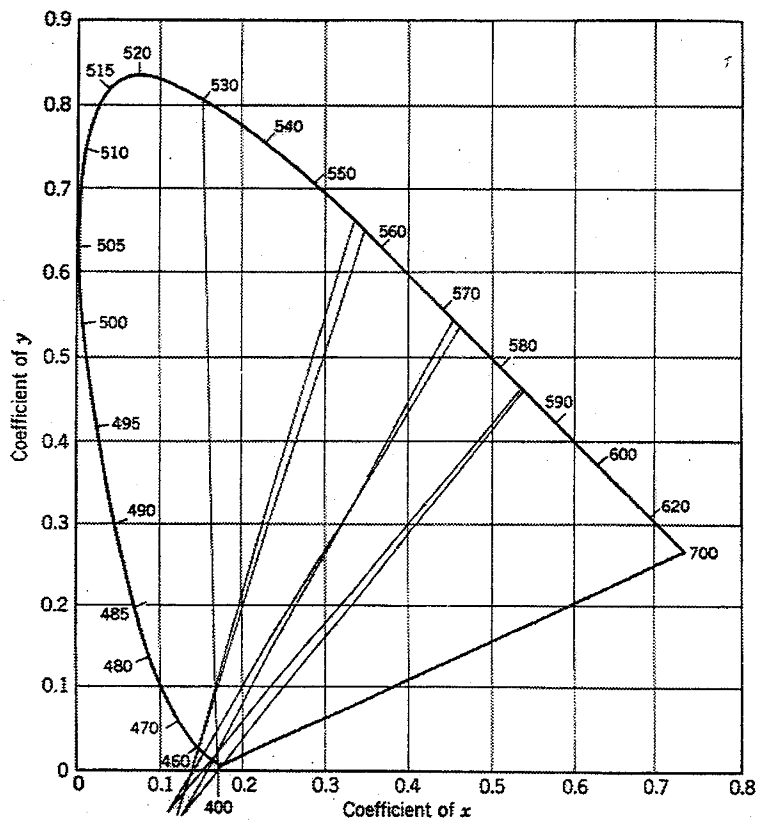

FIGURE 73. C.I.E. Color Space Diagram.

2. Only the location of the $\mathcal{R}$-$\mathcal{G}$ asymptote is shown to move. The movement of the other asymptotes is ignored. This is a direct result of the use of the classic three-cone theory of vision, which recognizes only one asymptote shift and does not even recognize it as a "null asymptote" but explains the known shift by movement of the cone overlap points [38].

[38] See Graham pp. 398-404; Wyszecki and Stiles pp. 900-935.

Unfortunately, comparatively little attention has been paid to the variation in movement of the other asymptote in the "normal" vision population, which is what concerns us here. If one looks at the distribution diagram of normal vision (Figure 72), one finds that the variation in "normal" vision is quite large, though its absolute magnitude depends somewhat on the study cited [39]

1. On the long (red end) side of the spectrum, the variation is given as

    a. A minimum variation of 24λ for the "normal normal" population cited by Coblentz and Emerson [40] in 1918.

    b. A maximum variation of 30λ for the entire "normal" population as a whole cited by Gibson and Tyndall in 1922.

2. On the short (blue end) side of the spectrum, the variation is given as

    a. A minimum variation of 16λ for the "normal normal" population cited by Coblentz and Emerson in 1918.

    b. A maximum variation of 20λ for the entire "normal" population as a whole cited by Gibson and Tyndall in 1922.

If one graphs the tolerance band for the "normal vision" population developed by Coblentz and Emerson used by the C.I.E. in the development of their 1931 standard color space diagram (accordingly adopted for use in this report in the name of consistency), one gets the tolerance zone shown in Figure 74.

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[39] Two items are worthy of note in this regard. First, the C.I.E. used Coblentz and Tyndall in deriving their standard. The calculations of this study followed the C.I.E. 1931 standard's example in this regard. Second, over the last 50 years as more tests were done, the limits have tended to expand. They now stand at 46λ, if one believes the maximum reported in the contemporary literature, which is not really comparable with the C.I.E. diagram and which if used would mean that the "normal variation" of the $\mathcal{R}$-$\mathcal{G}$ asymptote would cover about 85% of C.I.E. diagram. This is why it was not used in the calculations of this report, though it is worth noting that by modern standards the calculations of this report are on the concavities side.

[40] Actually given as a root mean square deviation of "nearly 4 mμ." (Cited from Le Grand pp. 109-110.)

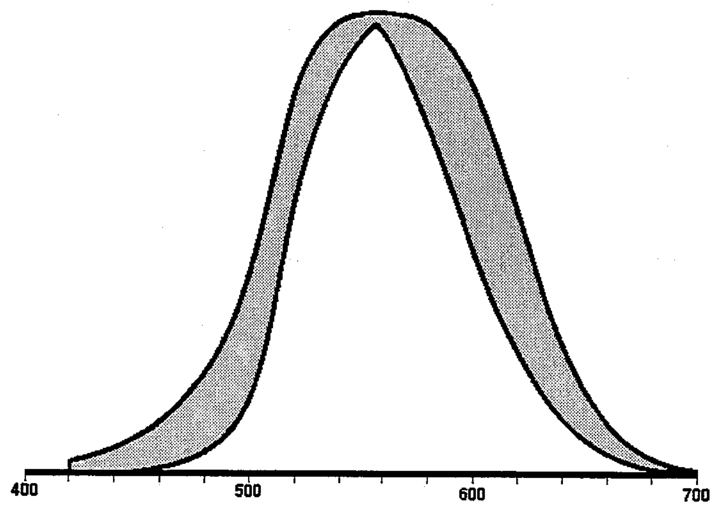

FIGURE 74. Tolerance Zone of Normal Vision According to Coblentz and Emerson.

NOTE OF STATISTICAL METHODS

Before continuing and putting the statistical variation of the asymptotes on the standard C.I.E. diagram, some discussion of the statistical method used is necessary. Almost all statistics taught below the Ph.D. candidate level are based on a one-dimensional bi-normal statistical universe, with only passing reference to the existence of higher-level statistical universe problems. Unfortunately, after some study of the problem and issues involved, the authors have come to the conclusion that the color vision variation involved here is, in reality, a "closed three-dimensional statistical universe problem." Because of the importance of the variation issue, the authors have chosen to treat variation as a three-dimensional parameter for the purposes of this diagram and its subsequent discussion.

The authors acknowledge that this decision of data analysis is a rebuttable presumption and that whether a variation is a one-, two-, or three-dimensional statistical universe parameter (in this case) is a debatable statistical mathematical issue, which will probably have to be resolved in the real world by analysis of actual experimental data. However, to us the phenomenon at issue appears, at present, to have the parameter characteristics of a three-dimensional statistical variable. One could argue that only $\mathcal{B}$-$\mathcal{Y}$ is a true three-dimensional variable and that $\mathcal{B}$-$\mathcal{R}$, $\mathcal{R}$-$\mathcal{G}$, $\mathcal{B}$-$\mathcal{G}$ are really only two-dimensional statistical universal parameters.

For the purposes of the average non-statistician reader, this means that the statistical distribution used in calculating the variation parameters is 27.8% tighter than the normal Gaussian one-dimensional bi-normal distribution he or she is used to seeing.. The tolerance limits are calculated as radiuses of standard spherical error (identified as $\dot{\sigma}$) the three-dimensional mathematical equivalent of "standard deviation" in a one-dimensional system, and then looked up in the standard three-dimensional statistical table.[41] From a functional point of view, this means that the variation is tighter and the percentage for a given variation higher than it would be if one had calculated it by the standard one-dimensional method. This fact that it is calculated as radiuses of spherical error accounts for the non-tripart division of the variation bars[42] of Figures 75 and 76.

Because of the importance of the variation parameter in this diagram, it was specially calculated in its three-dimensional form. This is not the case in the rest of the report. This is attributable to the simple fact that the normal spreadsheet and graphics computer programs used to generate the report did not include a three-dimensional statistical table in them, which makes such calculations manual and cumbersome (even though it might have been the more correct method in some places).

If one puts this "normal variation" on the standard C.I.E. color space diagram (Figure 75), one finds that the so-called "normal range" of available asymptote shift covers most of the diagram as shown in Figure 76.

A comparison of the test subject to the normal tolerance shift limits shows that a shift of 1λ or 2λ as observed for this test subject is all that is needed to account for the data problem. This represents a shift of only $\dot{\sigma} = 0.33$ or less than 1% of the maximum range reported for the "entire normal population." In this regard, the test subject is well within any statistical definition of "normal." The movement necessary to bring the null asymptote in line with the data is well within the limits of accepted variation of the normal population.

[41] Owen, p. 203.

[42] A three-dimensional statistical universe has only 4 $\dot{\sigma}$ in it to cover 99.9% of occurrences as opposed to the 6 σ of all standard one-dimensional systems.

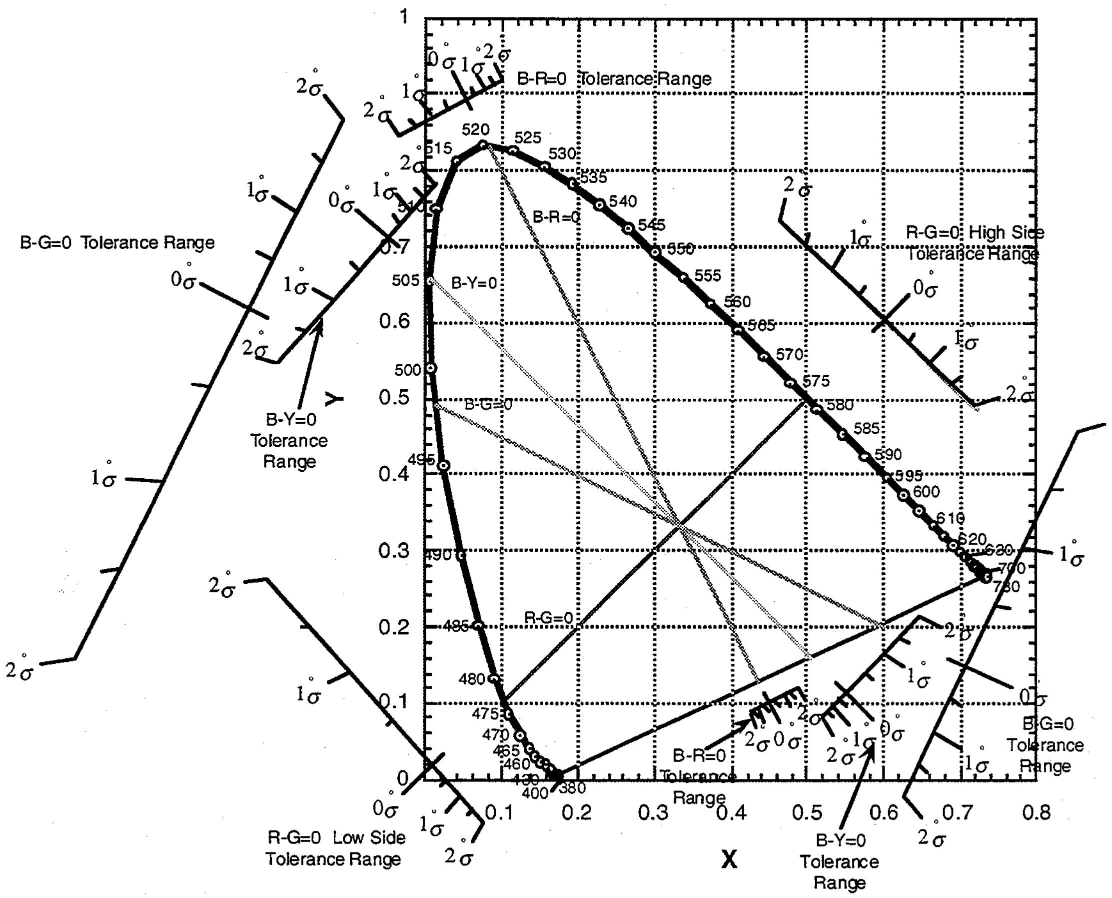

FIGURE 75. 1931 C.I.E. Chromaticity Diagram Showing Receptor Field Null Energy Asymptotes Tolerance Ranges.

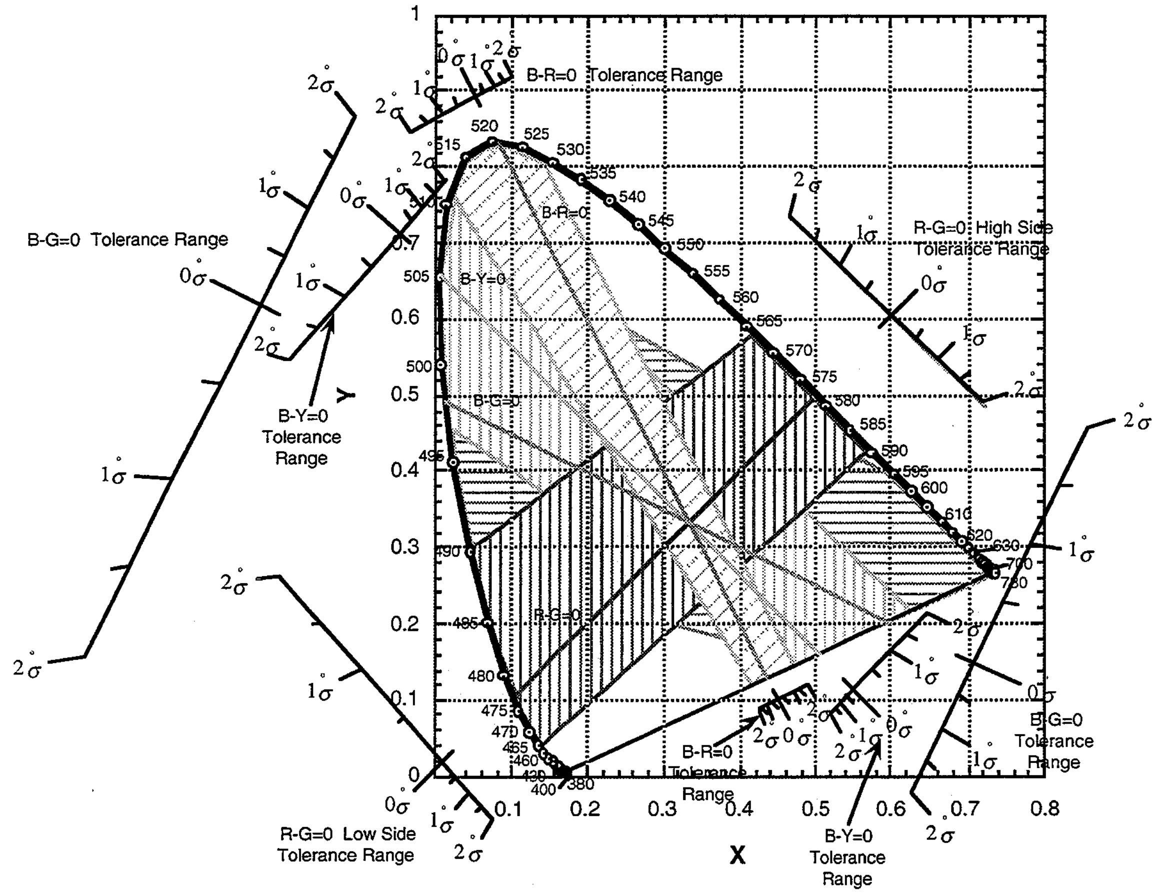

FIGURE 76. 1931 C.I.E. Chromaticity Diagram Showing Receptor Field Null Energy Asymptotes Tolerance Zones.

In defense of this movement of “norms” to meet the empirical test data (a position that some are bound to object to as improper), we would like to quote Le Grand, one of the principal researchers and developers of the 1931 C.I.E. standard. Le Grand, after a long chapter in which he very eloquently lists all the things that influence the location of points and distort the shape of his C.I.E. Color Space Diagram, gives a very eloquent denotation of future overridge adherence and use of his diagram. He states: “Colorimetery does not attempt to evaluate visual sensations numerically, but it does specify light physically, using the simplification afforded by physiological trivariance. This is clearly basic to the whole system, but once the standard observer is defined numerically, all men could disappear or become blind, and colorimetry would not suffer (except that it would cease to be of interest), because it deals with objective stimuli and not sensations.”[43]

[43] Le Grand, p. 170.

Le Grand did this, for he understood perhaps better than anyone else the elasticity of his C.I.E. model. Le Grand followed this statement with a two-chapter discussion of the difficulties of matching real observers with the theoretical standard.

It is our problem that we deal here not with "objective stimuli" but with the "sensation" that they produce in a real observer where the elasticity underlying the C.I.E. model is all important.

This elasticity not only permits the distortion of the C.I.E. standard observer models asymptote locations to meet an individual vision pattern (as we are doing here) but says that in all likelihood the spectral curve shape line probably is distorted somewhat for this test subject as well (something that the present experiment is incapable of determining).

In this regard, the authors believe that using the elasticity underlying the C.I.E. Standard Observer model to fit it to the individual is not only correct but is actually "the" correct use of the C.I.E. model and its underlying experimental database.

DYSLEXIA AND NORMAL COLOR VISION

In the somewhat boisterous debate that has followed Irlen's original assertion that dyslexia was the result of some color vision phenomenon, [44] vehement assertions have been put forward that this cannot be because dyslexics have "normal" color vision. While this often voices counter claim to the Irlen hypothesis, it skirts the issue of what one is defining as "normal," for much of the problem arises and depends on one's definition of normal.

For most individuals ascertaining that dyslexics have "normal" color vision, this means that they (dyslexics) have normal color response when measured by the standard color matching test, which is a reasonable if somewhat questionable assertion based on the nature of test. [45]

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[44] Irlen, 1983.

[45] For example, when Stiles did his study of field color matching, he found that a significant portion of his test subjects had a 25% to 40% reduction in perceived brightness in his color-matching test. This was subsequently overcome by Birch (Stiles and Birch, 1959) who found that by using flickering inputs, the problem would go away, and the standard color-matching procedure was subsequently altered accordingly. Based on the new flickering test procedure, both groups now are massed and defined as "normal" (largely because the test is specifically designed to produce that result). However, few would deny that there are two distinct sub-populations; nor is this the only case in the history of the development of the standard color-matching test where this has happened. One must recognize what the standard color-matching test is for. It is to define the most inclusive "normal population" possible. To do this, things like frequencies and test methodologies that have been deliberately selected to eliminate (therefore not identify and find) subgroups in a manner that they may be included in the "normal" population.

Based on the test data on this subject, one has to question whether the standard definition of normal is correct and not too all-inclusive. Although the dyslexic test subject in this experiment is well within the normal range of human color vision (but not modal), his color processing does not appear to be. This brings us to the somewhat disturbing question of whether the current definition of "normal" includes a number of distinct subgroups, which actually accounts for the wide variation in the generally accepted "normal range" of color vision perception.

The question that concerns us here is whether a dyslexic population subgroup of 10% to 20% of the total population is submerged in a modal population with a smaller deviation, which is actually causing the wide variation in the presently accepted definition of normal.

The present experimental data are capable of posing the question but do not answer it.

Part of the problem is that we do not know the ultimate physical source of the variation in the "normal" population. We can hypothesize several potential causes from reflector field structural theory, namely, that the cause of the "normal" population variation is one of the following:

1. **Change in Receptor Field Density.** Under this hypothesis, the entire energy variation noted in the "normal" population could be accounted for by a variation of ±19.88% in the density of either the inner or outer ring of the receptor field or any mutual change of the two fields that added up to that.

2. **Change in Receptor Field Size Diameter.** Under this hypothesis, the entire energy variation noted in the "normal" population could be accounted for by a variation of some 12.4% in the receptor field diameter of either the inner or outer receptor fields or a proportional change in the two that added up to that amount.

3. **Cone Dye Composition Variation.** We know from the work of Nathans that genetically induced variations in the dye in the cones can cause a change in the spectral sensitivity of the cones, [46] which could account for some or all of the variation in frequency sensitivity exhibited by the population as a whole.

[46] Technically, this has been shown to be the case only for the green cones. But this finding of mutant-based variations in the cone dyes can be extrapolated to the other cones without too much imagination or risk (Nathans, 1989).

The problem is that we have no idea if there is any correlation between these potential physiologically induced variations [47] and the phenomenon that we are observing in the dyslexic test subject with his non-modal color vision.

DYSLEXIA NULL ASYMPTOTES AND THE TEST DATA

This brings us to the subject of most interest in this area, namely, the relationship of null asymptotes to dyslexic color vision as revealed by this experiment.

If one looks at the null asymptote of the four receptor fields of the human eye graphed on the normal modal average C.I.E. Color Space Diagram, one finds that the fields are located as shown in Figure 70.

If one corrects the location of the fields to correspond to the apparent test result (as previously discussed), which, as noted, is well within the range of normal variation, the system for this dyslexic test subject would be as shown in Figure 71, with the location of the test points and corrected null asymptotes both shown.

If one analyzes this system against the performance plots, one finds the following:

1. The test subject suffers from massive changes in visual performance as the energy spectrum presented to his eye passes over a null asymptote threshold and enters a different section of the color space diagram (the sections of the color space being defined by their bounding of different sets of null asymptotes). In fact, if one looks at the performance diagrams and the data point location in color space, the test subject's eyes appear to be obeying an entirely different set of performance rules on one side of the null asymptote than on the other, or in a different section of color space.

2. This is particularly true of the $\mathcal{B}$-$\mathcal{Y}$ asymptote where the performance seems to change markedly from one side to the other, as with the $\mathcal{B}$-$\mathcal{G}$ asymptote where the performance again seems to change markedly when one crosses over asymptotic boundaries.

3. This also appears to be true of the $\mathcal{R}$-$\mathcal{G}$ asymptote in the area where blue energy ($\mathcal{B}$) constitutes greater than 42% of the total energy reaching the eye, but not in the area beyond the $\mathcal{B}$-$\mathcal{Y}$ null asymptote where red energy ($\mathcal{R}$) predominates.

[47] One can increase the list of potential physiological causes considerably if one wishes to. As noted earlier, Stiles work indicates that a 25% to 40% variation in the strength of color perception in the general "normal" population is as yet an unexplained phenomenon (Graham, pp. 389-390).

This shifting in performance from one side of the null asymptote to the other appears to occur for all the performance factors across the null asymptotes for each receptor field, although lack of data points in some of the asymptotic regions of color space makes this conclusion a tentative projection for them.

PRINCIPAL FINDINGS OF THE CAUSE OF PERFORMANCE GROUPING STUDY

The principal findings of the above inquiry of the cause of performance grouping are that for this test subject, visual performance

1. Depends on in what section of the eye energy chart the energy presented to his eye is. Sectioning of the chart is established by boundaries composed of the real null asymptotes of the test subject's eye.

2. Changes markedly when the receptor field energy changes sign.

3. Improves for certain performance attributes as the light spectral energizing the color vision system of the eye approaches a given receptor field null asymptote from a given side, although the individual result is dependent on which performance factor, what side of which asymptote, and in what color space zone one is.

The effect of sector performance for this subject is summarized in Table 11.

This marked visual performance variation dependence on color space zone and null asymptote location resulting from light spectral characteristics presented to the eye is something that has not been noticed in the vast majority of the non-dyslexic population in more than a century of color performance testing and is not reported in the vast literature on the subject. This absence leads us to believe that it therefore does not exist in the normal population at large.[48] We are led to believe that this peculiar condition of receptor field performances therefore is a direct cause of, or direct manifestation of, the condition that causes certain types of dyslexia in humans (or at least that subgroup of dyslexics identified by Irlen in her earlier work [49]).

[48] Admittedly a rebuttable presumption.
[49] Irlen, 1983, 1991.

TABLE 11. Effect of Dominance Groups and Receptor Field Types on Performance Factors.

Subjective factor	Dominance group domain	Effect on			
		R-G	B-G	B-R	B-Y
Reading speed	X	None But could be multiple	High positive correlation Gets better as B-G becomes less negative	Positive correlation Gets better as B-R becomes less negative	High positive correlation Gets better as B-Y becomes less negative
	N	High negative correlation Gets worse as R-G becomes more positive	None	High positive correlation Gets better as B-R becomes less negative	Positive correlation Gets better as B-Y becomes less negative
	Z	Two positive correlations	None	None	None
Focal length	X	None	None	None	None
	N	Positive correlation Focal length increases as R-G becomes more positive	None	Maybe	None
	Z	None	Positive correlation Gets better as B-G becomes less positive	Positive correlation Gets better as B-R becomes less positive	Positive correlation Gets better as B-Y becomes less positive
Angle of eye span	X	None	Positive correlation Gets better as B-G becomes less negative	Positive correlation Gets better as B-R becomes less negative	High positive correlation Gets better as B-Y becomes less negative
	N	None	Maybe	Maybe	Positive correlation Gets better as B-Y becomes less negative
	Z	Maybe	Positive correlation Gets better as B-G becomes less positive	Positive correlation Gets better as B-R becomes less positive	Positive correlation Gets better as B-Y becomes less positive

SUBJECTIVE FACTORS

At the beginning of this test, data on a number of subjective vision factors were collected. This was done essentially to acquire background data and was based on earlier anecdotal data reported by Irlen that some dyslexics affected by this condition reported these conditions. At the time of its collection, no real serious thought was given to analyzing these subjective data in a serious quantitative manner. They were simply collected as potentially interesting background data.

However, when these useless background data were subjected to analysis by the receptor field energy balance techniques previously, the data correlated to a remarkable degree, far beyond anything conceived or anticipated when the data were taken. The results of this analysis are presented in Table 12. The receptor field energy plots themselves are contained in Appendix E. This was done primarily to limit the volume of graphs in the body of the report, where the inclusion of 20 more graphical charts would not help the continuity of the document.

While it would be possible to work out formal statistical correlation factors and curve fit equations for these data and the various subjective factors that they represent, this is not really justified. The data are very subjective, and the analytical methodologies of both the receptor field analysis and statistical correlation analysis are two or three orders of magnitude more precise than the contents of the database. This means that while one can derive correlation factors and equation constants to three or four decimal places, anything beyond the first digit ±2 is really meaningless. As a result, this was not done. A general statement of the trend is presented instead, which is felt to be as meaningful of the results as presentation of the unreal formal mathematical results.

However, five items are worthy of specific note in the analysis of the subjective data. These are listed here.

1. That the correlations happen at all is noteworthy, even in this very subjective and impressive data, which is remarkable considering the nature of the database.

2. If one looks at the Clarity of Letters Versus $\mathcal{B}$-$\mathcal{G}$ Receptor Field energy plot (Figure 77), one sees an amazingly straight line in it.

TABLE 12. Effect of Dominance Groups on Subjective Factors for Receptor Field Type.

Subjective factor	Dominance group domain	Effect of			
		R-g	*B-g*	*B-r*	*B-y*
Brightness	X	Minor positive correlation Gets better as R-G becomes less positive	General*	Minor correlation Improves as B-R becomes less negative	None
	N	Minor positive correlation Gets better as R-G becomes less positive	None*	None	None
	Z	None	Minor correlation Get worse as B-G becomes more positive*	Minor correlation Gets worse as B-R becomes more positive	Minor correlation Gets worse as B-Y becomes more positive
Clarity of letters	X	None	Positive correlation	Minor correlation Gets better as B-R becomes less negative	Minor positive correlation Gets better as B-Y becomes less negative
	N	None	None	None	None
	Z	None	Minor correlation Gets worse as B-G becomes more positive	Minor correlation Gets worse as B-R becomes more positive	Minor correlation Gets worse as B-Y becomes more positive
Flicker rating	X	None	None	None	None
	N	None	None	None	None
	Z	None	None	None	None
Sustainability of focus	X	Minor positive correlation Gets better as R-G becomes less positive	General	Minor positive correlation Gets better as B-R becomes less negative	General
	N	Minor positive correlation Gets worse as R-G becomes less positive	General	General	General
	Z	None	General	General	General
Perception rating	X	None	None	Positive correlation Gets better as B-R becomes less negative	General
	N	Minor positive correlation Gets better as R-G becomes less positive	None	Minor positive correlation Gets worse as B-R becomes more negative	None
	Z	None	General	None	General

*There is a general positive correlation for the whole set: brightness becoming better as B-G becomes more negative.

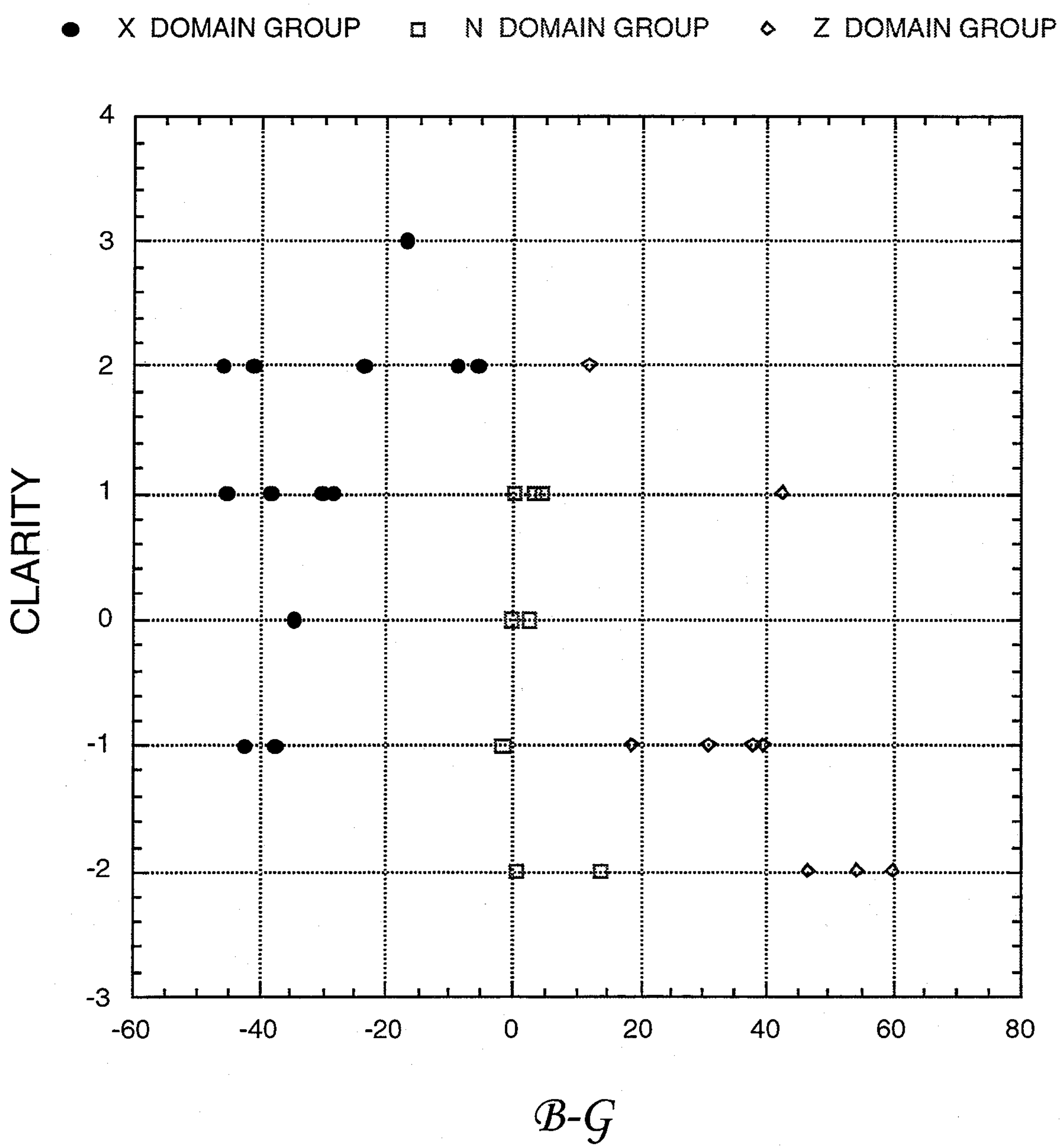

FIGURE 77. Rationalized $\mathcal{B}$-$\mathcal{G}$ Receptor Field Energy vs. Clarity.

3. The other thing worth noting in Figure 77 is that the two data points with the lowest negative $\mathcal{B}$-$\mathcal{G}$ energy level have fallen off the line and turned down. This has occurred at approximately $\mathcal{B}\text{-}\mathcal{G} \approx 17$ energy level, which is exactly the same point where focal length curve bent over and started to come down. This bend-over-and-drop-off phenomenon at a $\mathcal{B}\text{-}\mathcal{G} \approx 17$ energy level is even more pronounced in the sustainability plots (see curves in Appendix E). These are the best two reading speed points and this same bend-over phenomenon occurred at exactly the same energy point in all three energy plot systems (focal length, clarity of letters, and sustainability).

4. The same general trend that we saw in the reading speed, angle of eye span, and focal length energy plots occurs here, namely, that in a given domain set in an energy plot, that performance improves as the receptor field energy level in question approaches zero.

5. There is no apparent correlation for flicker. Based on this, we can tentatively state that flicker is not a receptor field energy- or a domain-dependent variable. Detailed analyses of the data tend to reinforce this conclusion. [50]

That these subjective data correlate and produce these conclusions must itself be considered remarkable and points out the strength of the underlying physical phenomenon.

EFFECT OF RECEPTOR FIELD DOMINANCE ON SUBJECTIVE FACTORS

If one graphs the various subjective factors (brightness, clarity of letters, flicker rating, sustainability of focus, and perception rating) against receptor fields by dominance group, one finds that the dominance grouping tends to move in coherent blocks. They also tend to move, in most cases, as one would expect with the non-dominant N and Z groups having all high values in some areas of the chart as the performance gets worse, roughly corresponding to the poor reading performance. Whether this is a cause or an effect is hard to determine. Even though the subjective factor data are rather gross and were never meant to be analyzed with precision, the analysis did reveal some interesting rough correlations. These can be summarized as follows:

1. Certain receptor field systems show no effect or correlation between their performance and a given dominance group (listed as none in Table 12).

[50] Detailed examination of the data shows there is no apparent rational pattern to them that conforms to the basis of analysis, which means either the database is too limited and variable to permit identification of its basis or that it is controlled by some other as yet unexplained factor.

2. Some receptor field systems exhibit a general correlation between the performance of a given dominance group where all the points of the group lie in some section of the graph, indicating general, poor, or good performance (listed as general in Table 12).

3. Some receptor field systems exhibit specific visible correlation between the performance of a given dominance group and positive or negative performance (Table 12).

The performance of various subjective factors for the receptor field systems by dominance group is shown Table 12.

POSSIBLE CAUSE OF OBSERVED PHENOMENON

While the present experimental database of one case is too small to draw any major general conclusion from, the test data present a tantalizing new option as a candidate for the cause of dyslexia. This option should be added to the already long list of possible causes of dyslexia, given in Appendix D.

The subject's visual system apparently likes a light spectrum presented to it that causes it to be essentially null or zero or very close to null in some receptor fields. Not only do the data show that reading speed increases as one approaches the null asymptote from one side in a given receptor field, but the angle of eye span increases markedly if the focal length is at its normal value, which occurs as the null asymptote condition is approached.

In Receptor Field theory, the following 16 matching positive and negative receptor fields are supposed to counterbalance each other:

+ R - G	- R + G
+ G - R	- G + R
+ B - Y	- B + Y
+ Y - B	- Y + B
+ B - G	- B + G
+ G - B	- G + B
+ B - R	- B + R
+ R - B	- R + B

It is impossible with the present experimental methodology to evaluate a mere sign change in the receptor field system. If physiologically one side of the balance was not there or proportionally diminished, it would account for the phenomenon we are seeing in the test subject. If the human vision system requires balance between such positive and negative receptors fields to process information correctly, then under a non-natural balance or shortage condition in the eye's physiological makeup, this could be supplied only by balancing the spectral energy to the eye to make up the shortage. The physiological verification of this somewhat speculative hypothesis will have to await work in advanced visual physiology. One can say of the hypothesis, if it were true, that

1. The math works out perfectly.

2. Running this type of color vision test/experiment on a normal individual without such a shortage would be impossible because his or her vision system would always be in balance and therefore the spectral energy shift in the incoming stimulus of the eye would have no effect. This appears to be the case in the vast majority of the normal population.

3. It would vindicate the empirically derived Irlen treatment technique.

4. This absence or shortage of balance in the receptor field system could well be a genetically transmitted trait that would correlate with the presently widely held view that there is a genetically correlatable component to dyslexia.

If the above hypothesis is essentially correct regarding the form of the basis of the physiological foundation of the problem, two other corollaries to the hypothesis would have to be considered:

1. If the opposite side receptor fields were not missing entirely or straightly proportionally diminished, but merely internally proportionally imbalanced, so that the counter field does not equal zero at the same point as its counter part but is off by some constant,[51] it would also produce a proportionally skewed energy balance (like that shown by this test subject).

2. If the previously stated were the case, it would mean that the null asymptotes of the two countervailing fields would not be cosynonymous in color space, a condition that would go far in explaining the apparent wide range of spectral frequency responses shown by Irlen-type dyslexics, [52] particularly if more than one set of counter fields were involved.

[51] Like an energy balance of 17, maybe?
[52] It would also go far to explain several abnormalities in the database of the existing experiments that to date have defied analysis.

COMMENTS ON EXPERIMENTAL TECHNIQUE AND FUTURE USE

Having spent the last couple of years massaging the data from this set of tests, we naturally have discovered that we did not run the experiment in an optimum manner and that we could design a much better experiment. (This is a course of events that will come as no great surprise to anyone who has engaged in large-scale experimental work.) Since some of these observations have a bearing on the validity of the experimental results, and/or would be of significant interest to researchers attempting to verify the results of this experiment and/or conduct more advanced research in the field, it was felt that some comments on experimental technique and the future use thereof were in order. These comments are presented below:

SOURCES OF VARIATION

When this experiment was started, we expected some "general" linear correlation between percentage of light energizing a given type of cone and reading speed. This correlation did not really occur. What we found instead was a far more complex system that is much more sensitized to change than anything originally contemplated. As a result, the experiment's design and analysis method suffers from sources of experimental error that were never originally contemplated. This shows up as excessive variation in the experimental data and results. These sources of variation can be divided into two broad categories: eye operation and experimental factors. These categories are discussed in the following sections.

Eye Operation

Several factors that were ultimately found to compose the "real" operation of the eye in regard to this type of dyslexia were significantly more sensitive than originally anticipated. This "significantly more sensitive" may constitute an order of magnitude or two more sensitive to energizing spectral energy levels than originally planned for. This was compounded by the fact that the analysis technique that was ultimately developed itself is probably an order of magnitude more precise than originally conceived and planned for.

The eye's receptor fields work from the difference in inputs rather than a simple linear function or linear summation. This makes it much more sensitive to change than one would intuitively believe. This absolute sensitivity shows up in a couple of places in the experiment rather markedly. For example, if one looks at the performance line slopes involved, one finds the following:

1. For the *B-G* Receptor Field plot for reading speed (Figure 45) in the X domain the increase in reading speed line slope is 1.078.

2. For the *R-G* Receptor Field plot for reading speed (Figure 48) for the negative side of the null asymptote, the performance increase in reading speed in the Z domain has a line slope of 4.83.

When one is dealing with equations in the form of $Y=4.8\ X$, one does not have a lot of room to vary X very much without affecting the results of the experiment significantly. This means that any error in the *R-G* parameter is magnified significantly. This sort of error rate magnification was not really anticipated in the experimental design and undoubtedly accounts for some of the variation in the test data.

Nature of Statistical Analysis

The other problem that one finds when analyzing this modification of eye operation is the fact that it turns out to be a trianary variable in which any error in one variable is multiplied into the other two. A degree of dependence not originally contemplated in the experimental design (though perhaps it should have been, coupled with the difference nature of the receptor fields operation, is enough to seriously affect results with very little real change being noted by the measuring system of the experiment.

The other problem raised by the trianary nature of the input variable is that it in reality probably makes analyzation of the resulting output a three-dimensional universe statistical analysis problem. While, as noted earlier, this is normally an area of discussion for Ph.D. candidates in statistics, in an experiment with this sort of multipliers in it, a truly serious question exists of whether the difference in results between analyzing the data in a normal one-dimensional binomial statistical universe versus a three-dimensional statistical universe system would be enough to affect the outcome of calculations.

While the authors do not think that the current experimental analysis is seriously affected by this problem, they will admit that certain types of statistical analysis were either not done or not presented because of the above question of statistical validity of the method of analysis. The authors do feel that the 27.8% delta (13.9% on a side) that can result from picking the wrong dimensional universe to work in is probably sufficient to affect the results of the

analysis of a larger array of points in color space, which is why the point is brought up and noted.

The statistical analyses done for this study were standard one-dimensional universe binomial calculations [53] (this was largely a function of computer power availability and statistical program capability), and this fact is believed not to have affected the gross results. The difference in statistical movement rates between a one-dimensional and three-dimensional statistical phenomenon is thought to account for some of the variation observed in the experimental results. This is really the result of people thinking in a standard one-dimensional binomial universe movement rate and tending to perceive and calculate the higher statistical movement rate of three-dimensional statistical phenomena as variation in their perceived normal one-dimensional world and calculations set.

The place where this is most noticeable in this experiment is in the performance of closely related points. A phenomenon in the world of standard text book color science is known as MacAdam Ellipses. [54] This phenomenon looks at how much of a difference in color a "normal individual" ought to be able to detect. If one looks at the location of our experimental test points in color space (Figure 70) and compares it to the standard MacAdam's Ellipses from any text book, one would be compelled to conclude that several of the points are so close to each other that the "normal observer" should not be able to distinguish between them. Yet, from our test data, we see major changes in the performance parameters between the two points, a fact that one can interpret in the following ways:

1. The result of the normal statistical spread in data gathering that one would expect in a human factors experiment.

2. The result of test area environmental factors (read uncontrolled background light spectral variation (as discussed in the following paragraphs)).

3. The result of a unknown integration relationship between the various receptor fields (also a possibility discussed in the following paragraphs).

4. The result of higher than expected statistical movement rates that exist because we are dealing with a three-dimensional universal statistical variable and analyzing it in a one-dimensional statistical universe, where the difference in movement rates show up as statistical variation in the one-dimensional calculations. (To avoid confusion in this area, it should be noted that the test

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[53] With the one exception noted earlier.

[54] This procedure is named after D. L. MacAdam who developed it and published his findings on the results on the sensitivity of color in 1942. See papers listed in bibliography for original source data. Most contemporary color science text books contain a reasonable synopsis. (Graham et al., pp. 391-392; and Wyszecki and Stiles, pp. 511-560.)

technique used in the original experiments to derive the McAdam Ellipses was a true three-dimensional methodology, as are the filters used in this test and Irlen's work on the subject. Most of the subsequent data used to fill in the literature base are derived from standard color spectral matching tests, which is a one-dimensional statistical test. In short, the literature database on the subject is not clear and may have the 27.8% variation in parts of it too, depending on which authority's test data one uses. [55]

5. A combination of all of the above.

The test data for this experiment were analyzed in the standard one-dimensional manner, which automatically assumes the first item is the source of all variation. The authors would not like to make any large bets on the subject in support of that thesis. Enough systematic error in the finer analysis of the data exists to cause one to question whether some of this apparent variation and the resulting "abnormalities" are not really the result of analyzing three-dimensional statistical data in a one-dimensional manner. The current experiment's data set is not of sufficient size or precision to determine this. The authors feel that in an experiment as sensitive to change as this one turned out to be, the 27.8% difference between a one- and three-dimensional statistical model, while insufficient to change averages and trend lines very much, is enough to affect confidence levels, correlation factors, and deviation limits to a higher level than one would like.

Interrelationship Problem

A major assumption of the physiology of Receptor Field Vision Theory has been that the different types of fields summed to some unified result in the vision processing centers of the brain. One of the major findings of this study is that this is not true for Irlen-type dyslexics. From the experimental variance point of view, the problem is that obviously an interrelationship exists that affects the results seen in the analysis. For example the positive side of the Z domain has

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[55] This is not quite as arbitrary as the above statement may make it appear. For under the classic three-cone theory of color vision, cone energization levels are a one-dimensional variable. The standard color-matching test, which was developed in accordance with this theory and is used to test it, is a one-dimensional statistical universe test, admittedly with three degrees of freedom, but still a one-dimensional statistical universe test. Much of the work that followed MacAdam used this standard color-matching test equipment. These experiments developed elliptical tolerance systems similar to MacAdam's on a classic three-cone theory basis. Such one-dimensional-based ellipse systems are widely reported in the literature, such as Stiles, Brown, and Wyszecki, and Fielder and are often presented on the C.I.E. diagram, as is MacAdams. This is usually followed by some discussion of the difference in findings between researches and by the various methods being presented. The difference in the statistical universe resulting from the test technique unfortunately is not usually one of the these. The MacAdam's data were used for comparison here because, like the filters of this test, they used a true three-dimensional variable technique, which corresponded more closely to this test's methodology and resulting data set.

a strong correlation for reading speed in the $\mathcal{R}$-$\mathcal{G}$ field plot, while the same relationship shows up as essentially uncorrelatable random noise in the other three field plots. In this case we can say that the $\mathcal{R}$-$\mathcal{G}$ field is obviously the controlling one for items in the Z dominant energization domain and that their performance placement in the other field plots is merely a reflection of their placement in the $\mathcal{R}$-$\mathcal{G}$ receptor field, even though at first glance it appears to be random variation. This same supposition can be made in several similar cases where asymptotes intervene and produce subgroups (discussed in the following paragraphs). However, it is very difficult in most of the more heterogeneous domain cases to say that one field set is controlling and that the apparent variation in the other receptor fields is merely reflections or that there is some fixed proportional relationship between their performance in two or more fields.

All we have to work with is a set of absolute performance outputs and if that absolute performance parameter is limited for some reason in one field, that limit is reflected in all the other performance field plots. That limitation might well be seen as "variation" in the data.

This limitation and reflection problem ultimately boils down to the question of how and why the receptor fields of this test subject function and interact the way they do. This question is to some extent addressed elsewhere in this report. One must recognize that one of major findings of this study is that the receptor fields of this dyslexic test subject do not act in a uniform integrated manner. The great question posed by this finding to visual physiologists is why that occurs. To that question we do not have an answer; it does not appear to be derivable from the existing data set. (Too limited and too much other variation probably can not be derived from the performance of a single individual test subject.) Our problem here is that without a “unified field equation” that relates and explains the interrelationship of performance in the various receptor fields to one another, one has great difficulty determining what is a real limitation in one receptor field being reflected in another and what is real experimental variation. All the reflections appear as statistical variation in the other fields.

Subgroups

As noted elsewhere, the major dominant groupings data may really contain subgroupings that are acting under a different set of performance rules than the rest of the major domain’s data points. Such independent subgroup performance would unfortunately show up as "variation" in the data, if unrecognized and accounted for. Based on the general findings of this study, one would suspect that points on the other side of a null asymptote from each other would act differently and that that difference in performance would be reflected as variation in the other receptor field plots. In at least two cases we

feel reasonably certain that this is in fact occurring, and in a couple of other cases it may be happening.

The problem is that we do not have enough data points in the potential subgroups spectral energy zone to be certain. In the case of the potential Z domain negative subgroup we have three data points. While in the case of the X domain potential subgroup we have two data points. In the case of the other two potential subgroups cases we have one data point each. The results are that if one sets out to determine whether what one is seeing is the result of the performance of independent subgroups or simply random variation, one is confounded by the lack of data. This fact not withstanding, one can run statistical tests on the data and come up with a reasonable supposition. Unfortunately if one looks at the data for the first two cases one finds the following:

Z Domain Group. If one looks at the two potential subgroups, one finds that the two sets of data do appear to work and correlate better, if they are divided up on the positive and negative side of the $\mathcal{R}$-$\mathcal{G}$ null asymptote. This can be seen by the increases in their correlation factors for the performance characteristics, as shown in Table 10, where the correlation numbers increase for the two sides in the $\mathcal{R}$-$\mathcal{G}$ receptor field plot rather dramatically and throughout the array, if the two populations are divided. The correlation study, therefore, shows that a reasonable probability exists that two distinct populations are working independently to their own rules.

On the other hand, studies show that the effect of excluding or including the two data sets in the angle of eye span versus reading speed analysis does not change the performance correlation line slope between these two phenomena of the entire Z domain data set by more than 6%.

The bottom line of this analysis, therefore, comes down to a firm maybe. While one can say that answer is probably yes, that two different sub-populations exist, there is really an insufficient number of data points to arrive at an unambiguous conclusion.

X Domain Group . Two data points (numbers 871 and 878) are to the far negative side of the $\mathcal{R}$-$\mathcal{G}$ null asymptote as can be seen in all the $\mathcal{R}$-$\mathcal{G}$ performance factor plots (Figures 48, 58, 53). The question is whether these two points are really of a different sub-population than the rest of the data points that form the X dominant domain data set, which are either very near or to the positive side of the $\mathcal{R}$-$\mathcal{G}$ null asymptote. [56]

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[56] The other points are probably all on the positive side of this individual's real $\mathcal{R}$-$\mathcal{G}$ null asymptote.

Again if one runs the correlation numbers with and without the subgroup included, the correlation of the larger group is better if the potential subgroup is eliminated, as can be seen in Table 10. However, if one does performance line slope studies on the effect of inclusion and removal of the potential subgroup on the various performance parameters and their interrelationship, one finds that, because of the location of the data points, the line slope change is minimal in all cases ranging from 0.3% to 12.3%, depending on which set one picks.

Similarly, the difference in movement patterns in these points between the $\mathcal{B}$-$\mathcal{G}$ and the $\mathcal{B}$-$\mathcal{R}$ performance diagrams (see Figure 78 and 79) would lead one to believe that they are in reality different populations. The result of this analysis is another firm maybe.

Other. In a couple of other cases one would like to test the hypothesis that the point is part of a different subgroup. However, this is not really possible because the potential subgroup is represented by a single data point, which makes running a valid statistical analysis unfeasible. Based on the general findings of this study, one would suspect that since this point is on the other side of a null asymptote from the main body of the data set it might be part of a different subgroup. Exclusion studies of these data points again indicate a maybe.

EXPERIMENTAL FACTORS

Environmental Lighting Effects

Probably the most significant source of variation in this test resulted from the fact that the lighting in the room where the test was performed was not controlled to an adequate level. The room had a directional incandescent light in it to provide light from the rear directly on the page. However, the room also had a window that admitted outside sunlight. Over the several-day period of this experiment, this extraneous sunlight contributed to the lighting environment of the room, which varied from direct sunlight entering the room, to blue background reflected sky, to shadow, to evening darkness. Both the test analysis procedure and collective sensitivity of the receptor field system of the eye turned out to be considerably more sensitive to spectral change than originally envisioned. As a result, little doubt exists that the uncontrolled environmental background lighting affected the test in a undesirable manner, which appears as an unaccounted for variation in the test data.

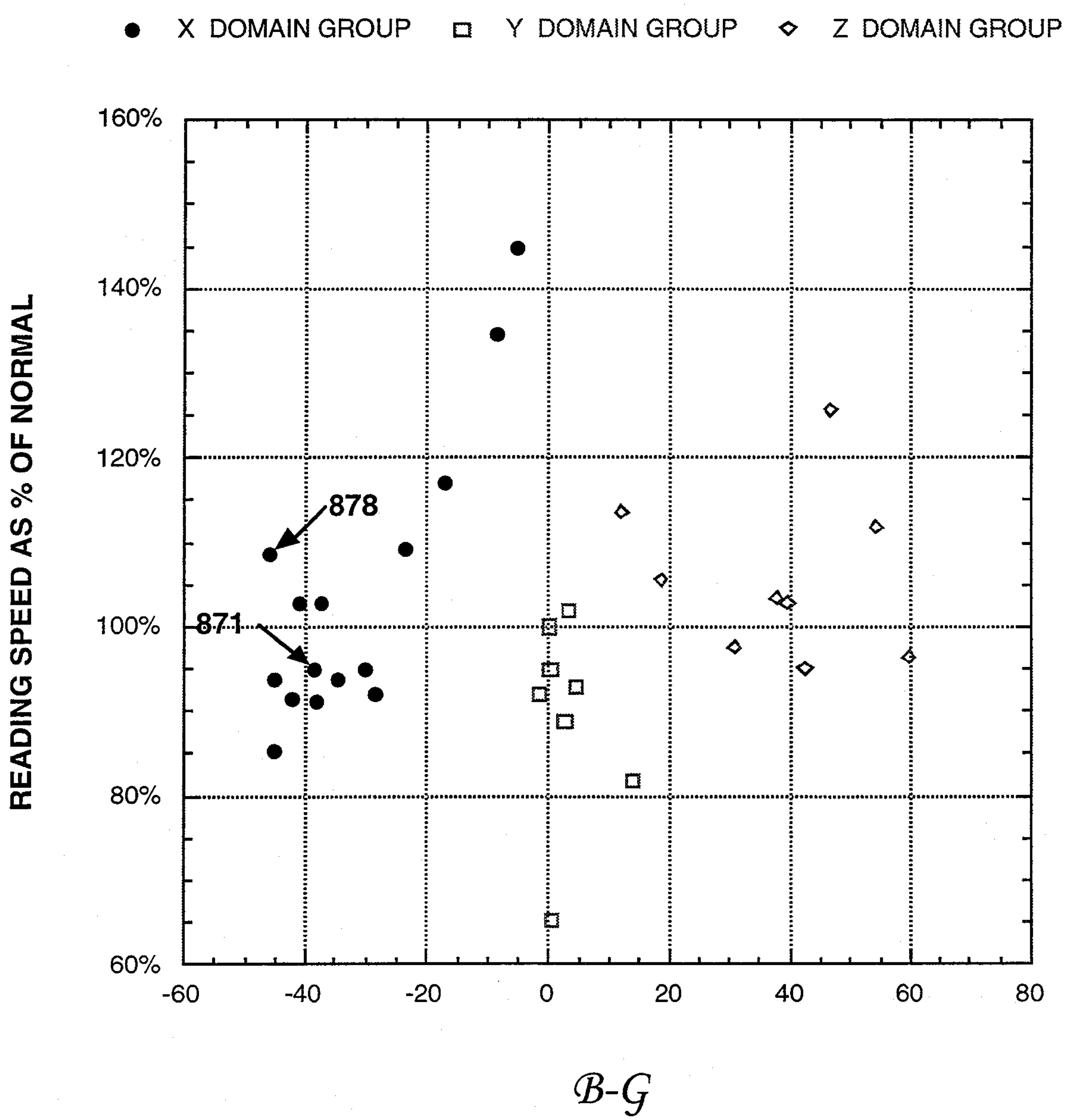

FIGURE 78. Location of Points 871 and 878 in Rationalized $\mathcal{B}$-$\mathcal{G}$ Receptor Field.

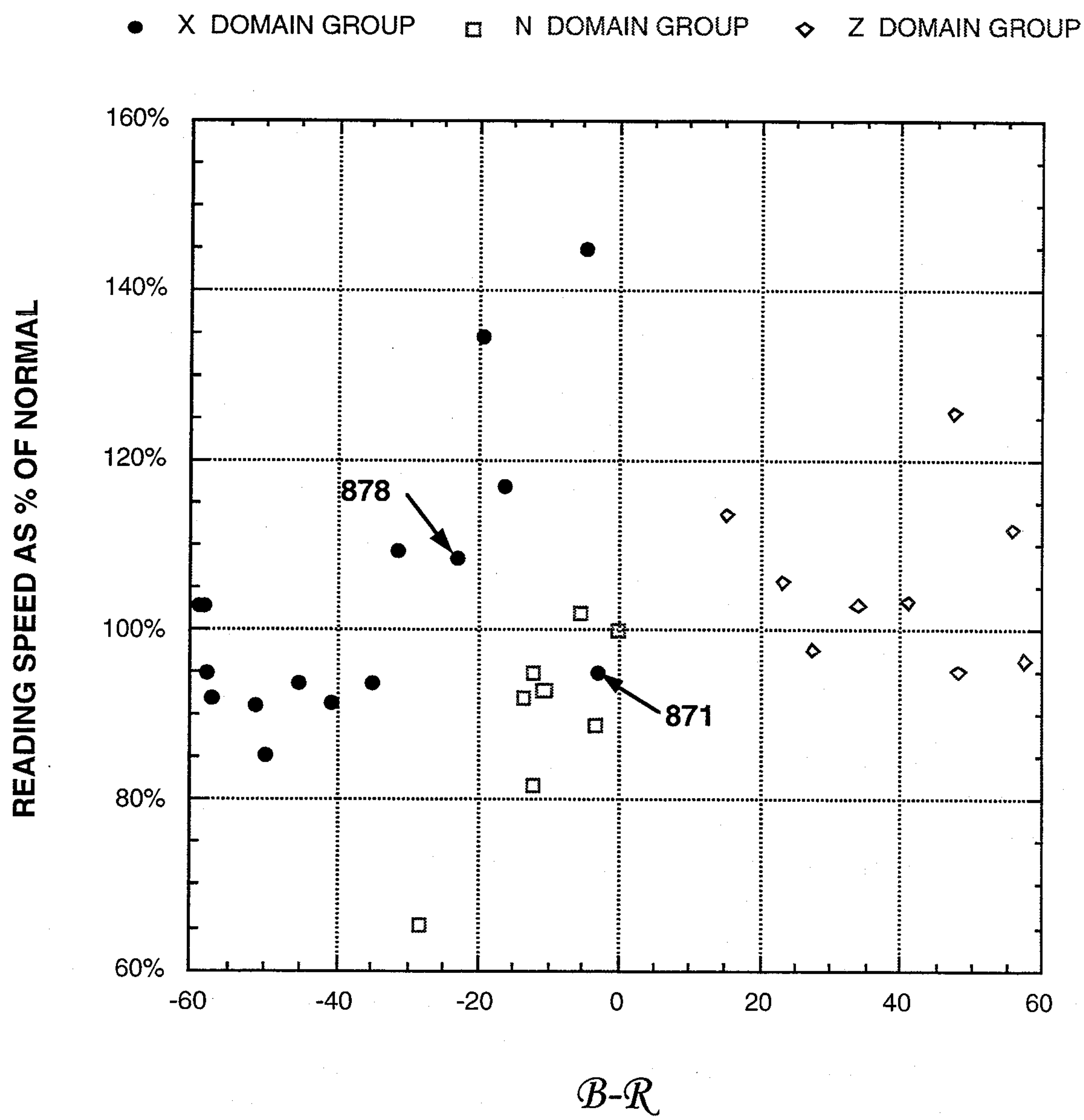

FIGURE 79. Location of Points 871 and 878 in Rationalized $\mathcal{B}$-$\mathcal{R}$ Receptor.

To further complicate the situation, the reading light was equipped with a rheostat that allowed the test subject to control the light level to a comfortable level. This, however, varied the color temperature of the tungsten filament of the incandescence light and thus its spectral composition. In retrospect, it was probably not a good idea.

Filter Curve Calculation Error

One other source of variation in the test results must also be considered, that is, the method used to derive the energy transmission effect of the filters. This was done with a computerized curve tracer called Data Thief (Version 1.0.7) developed by Kees Huyser and Jan Van Der Laan of the National Institute for Nuclear Physics and High Energy Physics, Netherlands. The resulting curve was integrated by a Simpson's Rule Technique. This procedure is by no means a perfect high-precision process. As a result, some systematic error may very likely exist in the filter curves reductions. This is felt to be on the order of 0.2 % for a given curve. Since such an error affects all the cone energy levels in the same systematic way, it probably results in a small proportional shift in the resulting receptor field calculations. However, this shift would show up as a systematic variation in the test results and a deviation from the systematic results in some cases. This deviation from a systematic result is possible on these filter curves where the Simpson Rule integration changes signs. This would show up as random variation in the test results.

The other problem that derives from the way the energy values were obtained from the curves results from limitations of the curve data itself. A number of the filter curves stop at 400 nm and a couple at 430 nm. This in effect cuts the tail off the blue curve value in the transformation calculation. In the original experimental scheme, this was felt to be of no significance. When the experiments calculations proved to be much more sensitive than originally envisioned, the question of the effect of this cutoff on the findings of the experiment reemerged. As a result, at the end of the experiments analysis phase, an evaluation of this cutoffs effect on the findings was run. The result of this evaluation shows that of the 43 filters available for use in this experiment, this condition affected 26, of which six were not used in the experiments calculations because they were too dark to read. This leaves 20 candidate problems. Of these, evaluation showed the effect of the tail cutoff was negligible in seven cases (less that 0.2%), insignificant in nine cases (less than 1%), and significant in four cases (the cutoff probably had an effect of greater than 1% on the rationalized energy balance calculation).

To judge the effect that the motion caused by the perturbations, review its effect on the $\mathcal{B}$-$\mathcal{G}$, $\mathcal{B}$-$\mathcal{R}$, and $\mathcal{B}$-$\mathcal{R}$ reading speed plots correlation. It was determined that in 28 out of the 60 cases the direction of motion caused by the perturbation would have improved the correlation factor. In 15 cases it would

have been irrelevant (these were largely Z domain points in B fields, which appeared to be noise anyway and the correlation was already so bad that minor movement of the type caused by the perturbation was irrelevant). In 11 cases no effect could be determined (these were largely N domain fields where the correlation was so poor that you could not tell whether the movement would be good or bad). In four cases the direction of motion produced no effect. In two cases the direction of motion would have made the correlation factor worse.

In four cases the size of the motion was judged to be significant (points 819, 832, 841, 842). In both points 841 and 842, the direction of motion caused by the perturbation was irrelevant in the $\mathcal{B}$-$\mathcal{G}$ and $\mathcal{B}$-$\mathcal{R}$ field plots correlation and would have improved the correlation factor in the $\mathcal{B}$-$\mathcal{R}$, field plots. For point 832 the direction of motion caused by the perturbation would have improved the correlation factor in all field plots. For data point 819 (which is the point with the worst problem—an energy balance change on the order of 4%), the direction of motion caused by the perturbation would make the correlation factor worse in the $\mathcal{B}$-$\mathcal{G}$ field plot and improve the correlation factor in the $\mathcal{B}$-$\mathcal{R}$ and $\mathcal{B}$-$\mathcal{Y}$. The basic pattern forms would not be affected significantly.

The conclusion reached on the basis of the preceding analysis is that collectively the perturbations caused by the filter curve cutoff problem would not alter any of the principal findings of this study to a significant extent.

Effect of Rays

One of the more interesting sources of apparent variation in the test data may not be one, but instead may be a manifestation of the lack of a full data set. There are a number of proportional ray traces in the data's filter set. (This is an unplanned quirk in the data.) The two most obvious ones are the two in the X-dominant domain set consisting of the following data points: 804, 805, 810, 806, 807, and 809 and 802, 811, and 813 shown in Figure 80. These sets of points represent proportionally balanced points in three-dimensional color space. If one looks at the individual points on the $\mathcal{B}$-$\mathcal{G}$ color plots for reading speed, one finds that it is these proportional ray traces that line up to make the central curve (Figure 81).

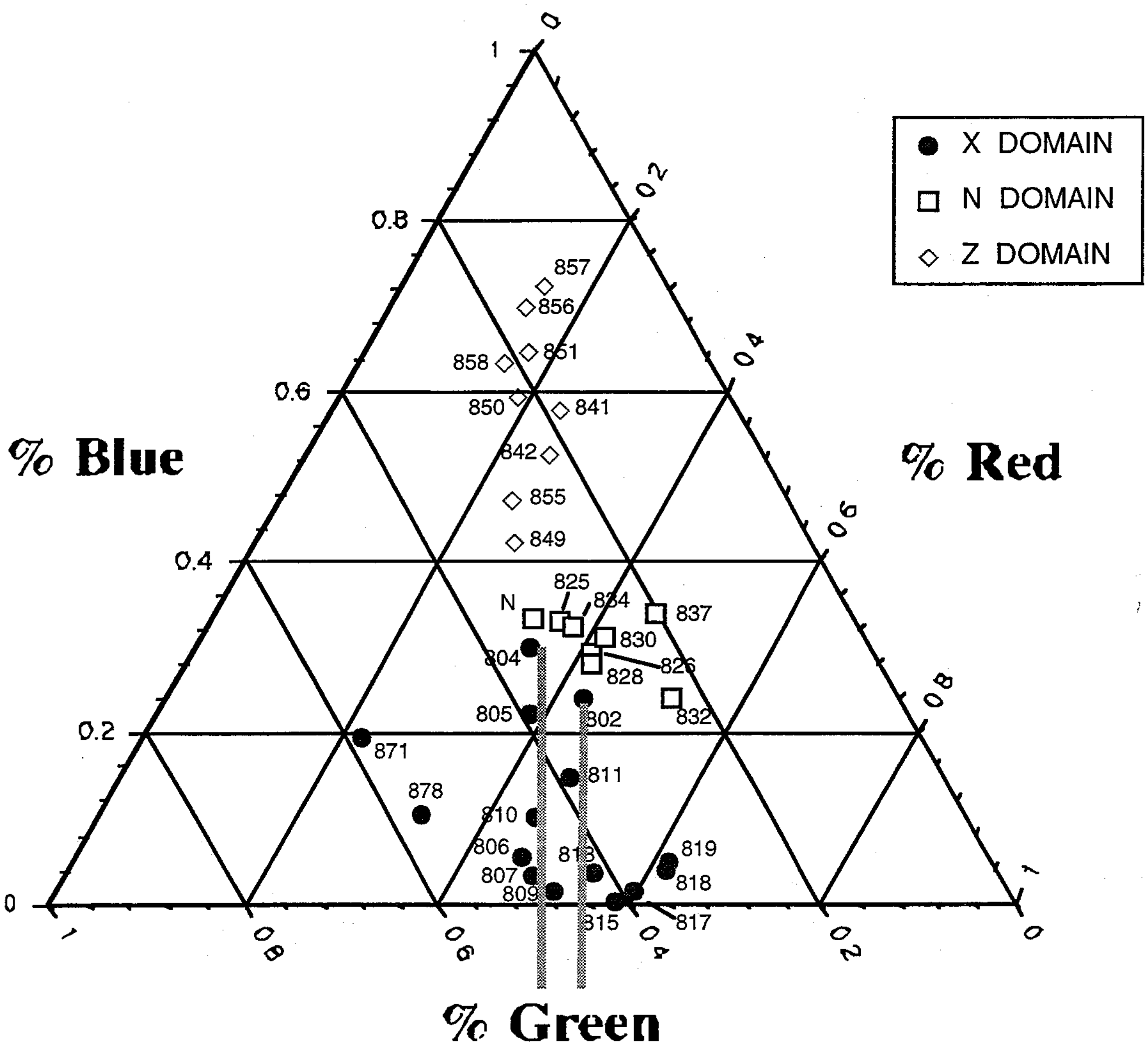

FIGURE 80. Ternary Percentage Plot of Filters Showing Potential Balance Rays.

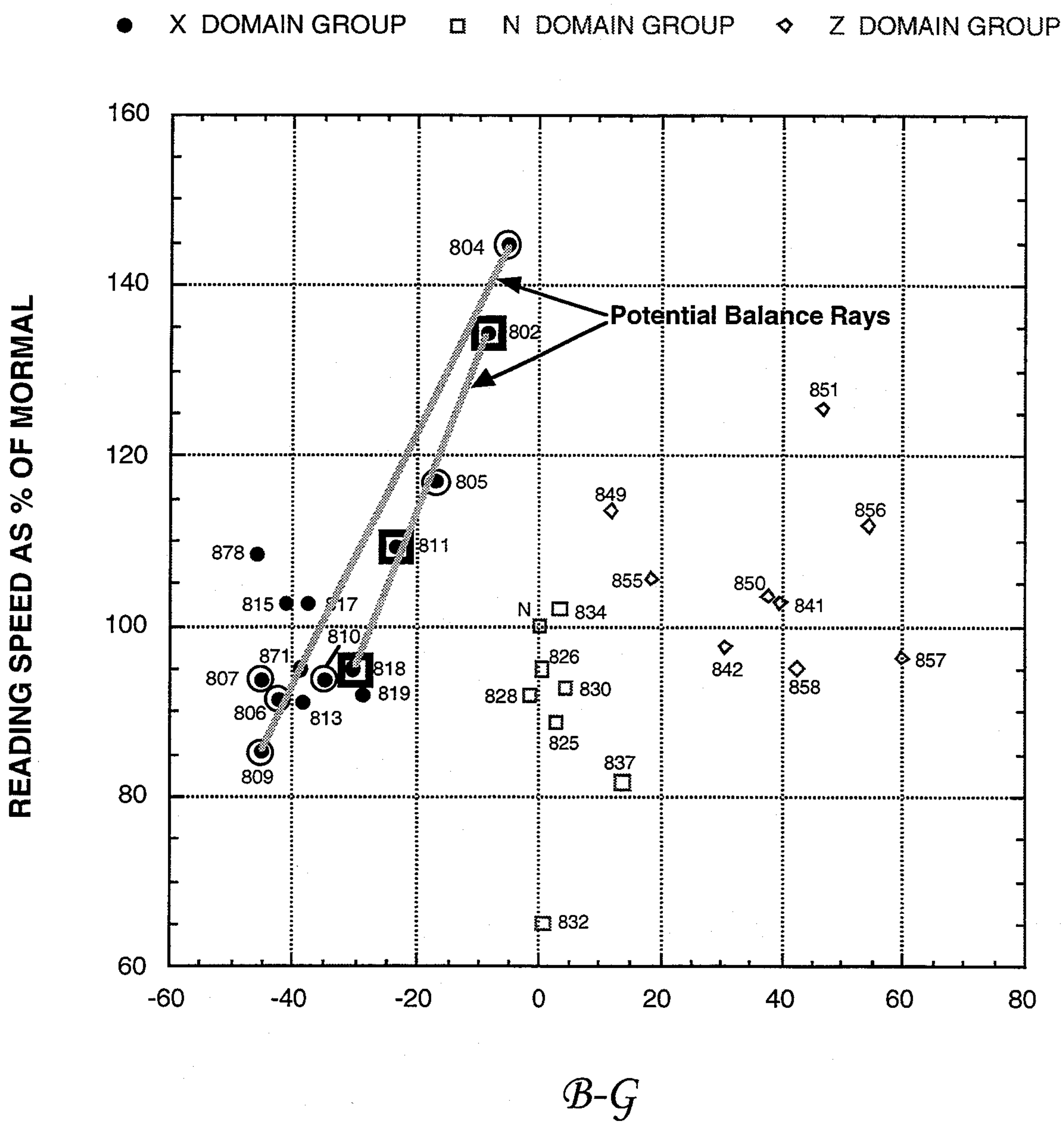

FIGURE 81. Potential Balance Rays.

If one looks at the same individual points on the $\mathcal{B}$-$\mathcal{R}$ plot for reading speed, one finds that the points of the two traces are still there but offset slightly (as they should be since the Y factor has been varied in a proportional manner). This leads one to the possibility that what we are really seeing is a family of curves moving through three-dimensional color space.

In a number of other places in the data if one plots the data points on the trianary consistency chart of Figure 41 or the C.I.E. color space diagram of Figure 69, and one starts following proportional consistency lines or equal energy lines (as they are called in the C.I.E. system) [57] around the diagram, one finds that some points seem to line up. The problem with the data set is that it has only two or three points on any given projected proportional ray line, and we cannot be sure that the lineup is a legitimate multi curve phenomenon showing up or just coincidence in the data, although there appear to be too many for mere coincidence.

This leaves us with the possibility that what we are looking at is really best described as a family of curves moving through color space of a given domain. In which case the points that show up as scatter are really not scatter but represent individual points on curves that we do not have the rest of. This shows up and as variance in our data plot.

This brings up the unpleasant possibility that if one had 200 data points in a domain rather than 20, one might not be able to find a general correlation by mass statistical analysis, because one would have so many data that they would mask the individual curves and their relationship to each other. However, a topology study or a three-dimensional tri-field consistency versus performance diagram might reveal the relationship. (One would need really good data.) However, there is a real possibility that, if such a relationship exists, it cannot be found by mass statistical analyses and would have to be found in a controlled experiment designed specifically to investigate its existence.

FUTURE USE OF EXPERIMENTAL TECHNIQUE

As noted earlier, this experiment started out as a preliminary survey to determine the validity of the Irlen hypothesis, that some dyslexics are affected by the light spectrum presented to their eyes, and to try to develop a methodology and technique to measure it, if it existed. Fortunately, this study has vastly exceeded its original intent and experimental design. This process has been both helped and hurt by a number of factors that are worthy of note by anyone attempting to use this technique or design an experiment based on it in the future.

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[57] A rather elaborate set of these have been built up in the C.I.E. color space system over the years.

Factors of Note

Four factors are worthy of note; three involve the filter set, and one involves the test subject. The color filter set selected for this test was a standard commercial set with both good and bad features, unknown and unrecognized at the beginning of the experiment. These features are listed in the paragraphs numbered 1 through 3. The fourth factor relates to the test subject.

1. The filter set did not give adequate coverage or have a sufficient number of points to

    a. Give a reasonable number of data points in each of the null asymptotes bounded regions of the eye in color space, and thus permit adequate analysis of performance in all regions.

    b. Permit isolation and bounding of the actual null asymptotes in the test subject's eye.

2. The color filter set had in it (by fortuitous accident) a number of ray lines of equal energy that helped greatly in the analysis and without which a considerably more complicated and sophisticated statistical analysis would have been required to identify and isolate the performance parameters within each region.

3. The color filter set had in it an essentially blue equal zero filter at almost the center of the maximum visual performance line through color space for the test subject. This fact greatly facilitated analyses and must be regarded as a quirk.

4. The test subject for this experiment came from the "narrow visual angle Irlen subgroup," one of four to six subgroups previously identified by Irlen. This resulted in the attempt to measure the angle of eye span, which in turn led to the discovery of shifting in the focal length. This in turn gave us three physically quantifiable factors as opposed to just one (reading speed), a fact that greatly facilitated analysis. This test result might be much more difficult to reproduce in the other Irlen subgroups simply because one cannot find another reasonably quantifiable set of performance factors to measure. While this analysis shows that the other subjective factors (which appear to be most important to these subgroups) are quantifiable and capable of being analyzed, the level of precision available in measuring these factors are an order of magnitude or two less than is available from the physical focal length and angle of eye span measurements. Furthermore, most of these facts call for subjective judgments on the part of the test subject, which may vary markedly between individual test subjects. This may make it difficult to apply the analysis technique to the other subgroups, unless one can find some other parameter to measure and quantify precisely, though raw reading speed should still be available for all subgroups.

Reproducibility

The modern scientific method says that to be legitimate, an experiment must be "reproducible." The data from this experiment are reproducible with the given test subject: that test check was performed and the results are within acceptable experimental limits. The wider problem is that the test subject is abnormal and is, in effect, a member of one of probably six Irlen symptomatology subgroups previously identified, this makes the experiment difficult to reproduce unless one can find an equivalent abnormal who is part of the same Irlen subgroup on whom to run the experiment. This may be more difficult than one would initially envision.

If we look at the question of reproducibility on a larger scale, we find the makings of a major problem. We know from anecdotal and empirical studies done by Irlen that there are individuals who like high negative energy levels as opposed to low ones, such as this test subject, as well as individuals who like high positive energy levels. [58] Obviously, if one runs this type of test on one of these individuals, one is going to get a different result than the one derived on the present test subject. Though vision will still vary with energy level, it will do so in a different manner. In short, the method will work, but the results will be different, depending on the nature of the test subject.

The authors believe that if enough individuals are tested, the data will ultimately cluster out into finite recognizable groups with coherent statistical characteristics. We are, at present, confronted by the unpleasant fact that, until these symptomatic clusters are identified, we will generate a lot of individual test cases that appear to be unique and uncorrelatable to each other. This is because we are really looking at members of different sub-populations without knowing where they fit in the grand scheme of things.

The central findings of this study are that Irlen is correct that visual performance of dyslexics does change with the frequency composition of light input into their vision system and that the reason for this lies in the receptor field system of the eye (and/or its output processing). Beyond this is the question of the total number of types of receptor field variations that can manifest themselves as effects in visual preference. The answer to this is unknown at present, but it is probably now the paramount research question and the fundamental block to understanding the full scope of the problem. Unfortunately no isolated data point test, such as the one conducted here, can answer this question. It will require some reasonably sized database. In this regard we are confronted with two significant problems:

1. The first problem comes as a result of a frighteningly large number of cases that are possible in the makeup of this distribution. If one holds that there

[58] A hypothesis that has been verified at a rudimentary experimental level by this investigator.

are really 16 physiological receptor fields (the currently generally accepted position) and one of them is defective and causing the problem, one would end up with 16 energy variant sub-subgroups. On the other hand, if two fields are bad, one would end up with 120 sub-subgroups. With four bad fields, one would end up with 1820 sub-subgroups, and beyond four one is not going to like the numbers very much. To these numbers one must also add the possibility of rod intrusion and total energy variation effects to the matrix (which cannot be ruled out on the basis of this experiment), which could add another 20 factors to the array. This increases the probability numbers of sub-subgroups by a couple of orders of magnitude.

2. The second problem that grows out of any attempt at present to estimate the number of combinations that might exist in the population is that this is liable to be quite difficult to verify, considering the fact that the condition affects 12% to 20% of the human race, a population so large that any possible physiological variant that can exist, will exist, in some finite group of the population. In fact, the mathematical probability of this occurring is $\sigma = 5.99781$, which is about as close to certainty as one comes in the real world of applied mathematics. [59]

The problem from a scientific proof and verification standpoint is that without better knowledge of the clustering of the population (which we do not have at the present moment), one will have difficulty reproducing any given experimental result because one would need a test subject of the same sub-sub-subgroup on whom to conduct the experiment. At the present time, we do not know how to select such a subject other than to run the experiment until we find a match, a not very effective or legitimate way of running an experimental test program.[60]

In short, exact reproduction and verification of any given set of experimental results are going to be difficult because of the number of unisolated potential variations causing clustering and subgrouping.

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[59] Owen, p. 12.

[60] In the case of these test data, one does have an option—to pick an individual of the same subgroup who likes yellow-green light and does not see well in blue, red, or violet. Though it will probably verify the results, it is still not a very legitimate experimental technique.

From the point of view of the larger question of experimental metrology, an analysis of the potential variation and clustering problem is required. The scope of the problem says that the number of potential subgroups is so large that neither group theory or multivariable statistics will probably be able to reduce the problem to a closed set any time soon, and that the proper method of analytical attack is to take the Irlen four to six symptomatology groups and apply a group theory analysis to their symptomatology sets, to define the sets and their overlaps and then apply progressive branching theory to identify their major subgroups and symptomatology elements. It is felt that this is probably a considerably more rational approach to attacking the problem by en masse statistical analysis on a few dozen data points trying to identify and fit them into a couple of hundred subgroup clusters, the parameters of which we have not yet identified.

GENERAL SUMMARY OF FINDINGS

GENERAL FINDINGS

This experiment shows that the Irlen effect is real. The energy spectrum presented to the eye of a dyslexic is capable of altering his or her visual and cognitive performance to a significant extent (for both better and worse).

QUANTIFICATION STUDY FINDINGS

By varying the energy spectrum presented to eye of this dyslexic test subject we were able to produce a reading speed variation of 80% of normal with reading speed varying from 65% to 145% of normal.

This reading speed variation is not an independent variable, but is ultimately caused by changes in angle of eye span and focal length, with significant changes in these parameters resulting from the spectral energy shift presented to the eye's vision system. The angle of eye span varies from 48% to 248% of normal and focal length varies over a range of 4.9 inches, which represents a change from 87% to 122.7% of normal over the spectral range used in this test.

This wide range of change in focal length was a totally unexpected phenomenon, lying outside the bounds of anything predicted by the normal theories of human vision or reported in the scientific literature on the subject. It may represent a unique characteristic of this type of dyslexia.

The various subjective factors (brightness, clarity of letters, sustainability of focus, and perception rating) also showed a general correlation with reading speed, generally getting worse as reading speed deteriorated and better as reading speed improved.

Several of these subjective factors also appear to moderately correlate with each other.

RECEPTOR FIELD ANALYSIS FINDINGS

Under the Receptor Field Theory of Human Color Vision the cones of the eye are organized into a set of counterbalancing fields. The balance output signal of the individual fields is the vision signal transmitted by the optic nerve to the brain for processing.

If one reduces the energy spectrum presented to the test subject's eye by the filters into components corresponding to the individual cone dyes energy absorption response and then feeds those data into a mathematical model of the receptor field system, one is capable of simulating the output signals of the test subject's vision system to the brain's visual processing center.

If the data from this experiment are analyzed within the framework of the modern Receptor Field Theory of Human Vision in this manner, the data correlate to a remarkable extent. The correlation of the quantifiable performance factors (such as reading speed) reaches the 0.8 to 0.9 range, producing the results shown in the following section.

Separation into Domain Groups

The data set for this test subject and experiment divides into the following three groups based on the energy domain of light reaching the eye:

1. A group dominated by energy in the (red and green) cone region
2. A group where no single cone energy level is dominant
3. A group dominated by energy in the blue cone region (where blue energy is more than 42% of the total energy available to the eyes vision system)

These energy domain groups act in a coherent manner among themselves, obeying their own internal rules of performance.

Performance Factors Analysis

The quantifiable performance factors (reading speed, angle of eye span and focal length) vary within their domain groups based on their energy level within a given receptor field, with correlation factors running in the 0.8 to 0.9 range for reading speed and angle of eye span.

It appears that one receptor field is performance governing for any given domain group, with different receptor fields controlling performance in different spectral energy input ranges.

Generally, visual performance improves within a governing receptor field as the energy level approaches zero or null from one side.

One gets better performance if more than one receptor field energy level approaches zero at the same time.

One gets better reading speed and angle of eye span performance as the focal length approaches its normal value and one has a low governing receptor field energy. Stated conversely, performance deteriorates as the focal length deviates from its normal value.

The behavior of the different performance factors appears to be entirely different on the positive and negative sides of the zero point of a receptor field (or null asymptote).

This receptor field energy versus performance phenomenon represents one of the major findings of this study and is a previously unreported phenomenon.

Reason for Domain Grouping

The domain groupings appear to be the result of the spectral energy reaching the eye being in regions of color space bounded by a given set of receptor field null asymptotes.

It appears that, in this Irlen-type dyslexic test subject, the receptor field system as a whole does not sum to a unity, but that the individual receptor fields act independently. This is not in accordance with generally accepted reflector field vision theory, which has held that the sum total of the receptor fields outputs sum to a unity in the vision processing center of the brain.

If subsequent research on other individuals and other Irlen subgroups verifies these findings as a general phenomenon for Irlen-type dyslexics, it will represent a major new and previously unreported factor of great significance to understanding the basic cause of dyslexia. It will perhaps provide a major new avenue for inquiry and study into the understanding of normal human vision as well.

Subjective Factor Analysis

The subjective performance factor data that were originally taken merely as background information correlate to a remarkable degree, when analyzed by the same receptor field method. This analysis produces essentially the same results. Lower energy in the governing receptor field is better with reasonably high correlation factors, considering the subjective nature of the data.

This occurred for all subjective factors, except flicker, which does not appear to correlate with anything.

Variance Analysis

It appear from these test data that the dyslexic test subject's vision system is much more sensitive to change than one would expect. Significant performance variation takes place at energy variations so small that the individual should not be able to detect the color variation involved, if the normal MacAdam's ellipse color perception theory is applied to the changes in spectral energy composition. While this finding is somewhat tentative because of the high experimental variance in the data, it is supported by the present data set.

GENERAL CONCLUSIONS

The Irlen spectral energy input modification method is capable of being used to mitigate the effects of dyslexia in some individuals.

The Irlen therapy approach to the treatment of dyslexia does have a rational scientific basis, based on the Receptor Field Theory of Human Vision.

The experimental methods developed by this study can be used to quantify the performance of Irlen-type dyslexics and to study the impact of visual spectral energy inputs on their vision system.

MILITARY IMPLICATIONS OF FINDINGS

This study, which verifies the existence of a new human factor element that affects 10% to 20% of service personnel, has a number of implications affecting training, use, and performance of military service personnel. Areas of potential military impact include the following:

1. The original question asked by the NAWC Fleet Training Support Office sometime ago, whether this phenomenon (scotopic sensitivity syndrome in dyslexics) could affect training efficiency of naval personal, can now be answered: yes. It would appear, based on this study, that 10% to 20% of naval personnel (probably concentrated in the low-end performers) could be helped to perform better by paying attention to their special needs regarding lighting and frequency response of the report of printed matter used in training. This would very likely significantly improve the performance of this subgroup of the training population at minimum cost and with no adverse effect on the majority of the training population.

2. In the 1950s the U.S. Air Force conducted an extensive study regarding whether pilots could see better through yellow visors (then popular) as opposed to clear ones.[61] This was a subject of debate at the time and the Air Force concluded that in reality there was no difference and that better sight through the yellow visors was just an old wives' tale. Based on the findings of this study, we must conclude that the findings of the Air Force study were incorrect, in that some limited finite subgroup of the population (of which this test subject would be one) would see better though yellow visors. Furthermore, based on the findings of this study and work done by Irlen, one could conclude that in all probability some 10% to 20% of the pilot population would probably see better and perform better if they were tested and provided with visors specifically marked to the characteristics of their individual receptor field system.

3. It would appear from the findings of this study that some significant portion of the Navy's personnel [62] would be able to perform operational tasks better and with higher efficiency if their lighting environment were attuned to

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[61] Widdel and Post, pp. 159-161.

[62] The exact number of naval personnel in this category is somewhat difficult to judge. The estimate of dyslexia in the general population is 10% to 15% (with 12% being given as the normal average). However, people with this problem tend to migrate to work environments that mitigate their handicap. This often means action-type jobs (of which the Navy would be a good choice), so the naval force affected by this condition might be higher than the national average. In addition there are those who claim that dyslexia is a continuous phenomenon spread through the population and that only the lower end of the distribution notice the problem. Therefore, a much larger group than normally envisioned is really affected by a moderate level of this problem. (Based on the findings of this study, the authors would question this assumption, but will concede that an unknown moderately affected, portion of the population might be larger than is ordinarily envisioned.)

their personal needs. This might have to be done by the individual Irlen method.

4. The military services have traditionally been one of the leaders in screening personal for physical and physiological attributes in order to place them in a work environment where their unique personal talents and capabilities can best be used. The testing procedure developed by this study provides a new avenue for screening and selecting military personnel for placement in environments where their natural talents and abilities can be put to optimum use. This avenue would avoid assignment of personnel to those operational environments where their visual performance parameters would cause them to inherently perform badly, thus putting the mission, naval assets, and/or other personnel at risk.

In this regard this study and earlier work by Irlen shows that the visual processing condition known as Scotopic Sensitivity Syndrome can adversely influence an individual's efficacy and performance under certain lighting conditions in a previously undetected and unsuspected manner. For example, the current test subject would probably see better and perform better in a low-pressure sodium lighting environment or under red battle lighting as opposed to a runway blue or a mercury vapor lighting environment. Knowledge of this personal attribute, once identified through screening, could then be used to place personnel in work environments most conducive to their individual optimum performance. Such knowledge would also permit modification of the individual's work environment, such as modifying the color display of a cathode ray tube (CRT) output to achieve maximum individual performance.

5. The results of this study demonstrate that there is the possibility of significant improvement in the performance and efficiency of a sizable portion of naval service personnel (maybe 10% to 20%) through modification of the work environment lighting system in which they perform their duties. This probably could be done with relatively minor effort and at relatively low cost.

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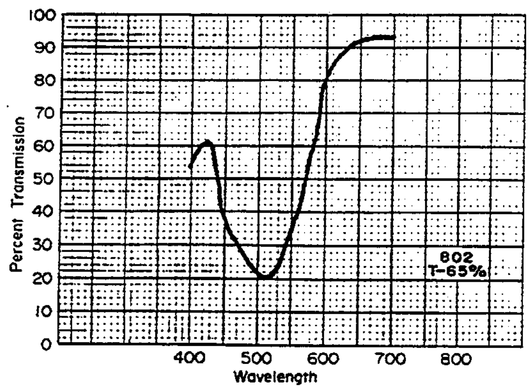
Appendix A
SPECTRAL CURVES FOR FILTERS

Filter 801 was a clear frost; it had no spectral curve in that it was fully transparent to the optical spectrum. It was used in the test by the test subject more or less by accident, because it was in the filter set (no one told him not to use it).

The results, however, were quite unexpected. Eye span went up and reading speed went down, which does not generally fit with the rest of the data. While some consideration of throwing the data point out were entertained, it was decided to retain it because it demonstrated the serious need for studies to determine the effect of the quality of light for individuals suffering from the Irlen phenomenon.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Wavelength
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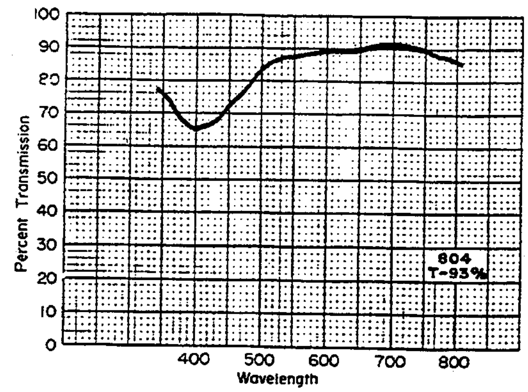
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Wavelength
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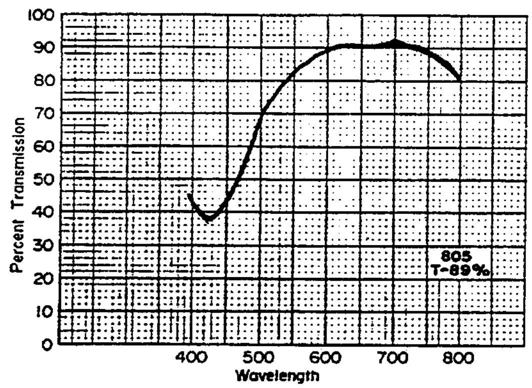
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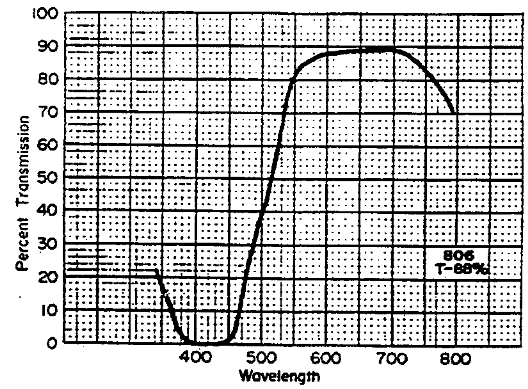
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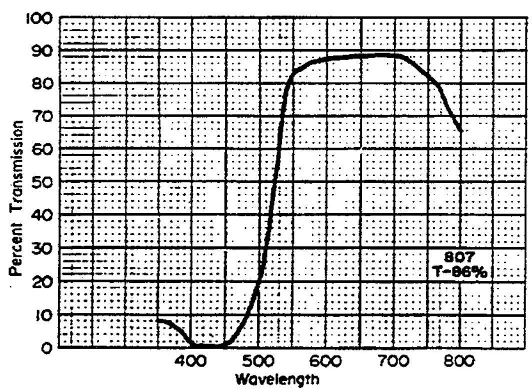
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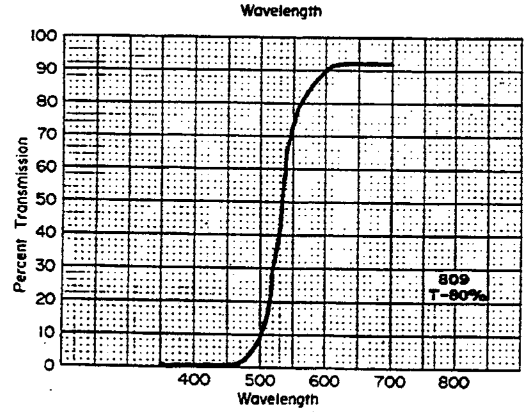
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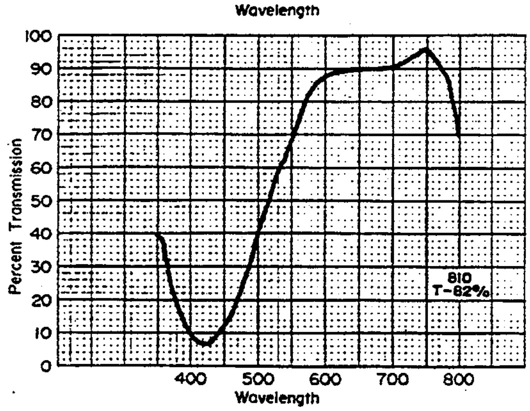
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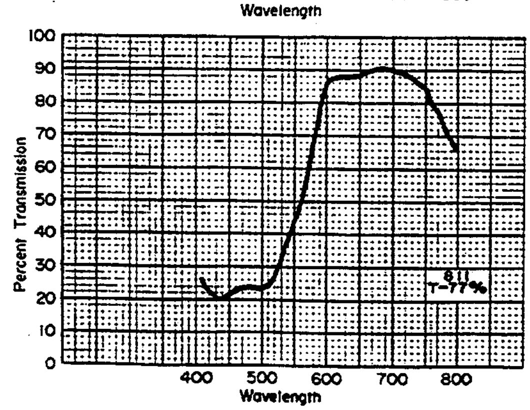
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Wavelength
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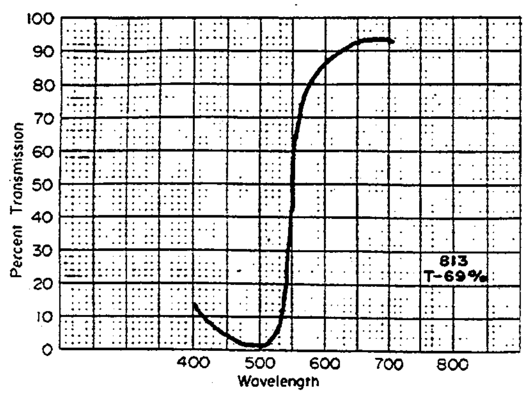
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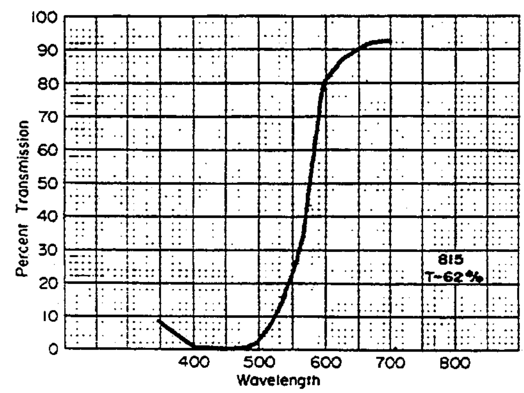
Wavelength
813
T-69%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Wavelength
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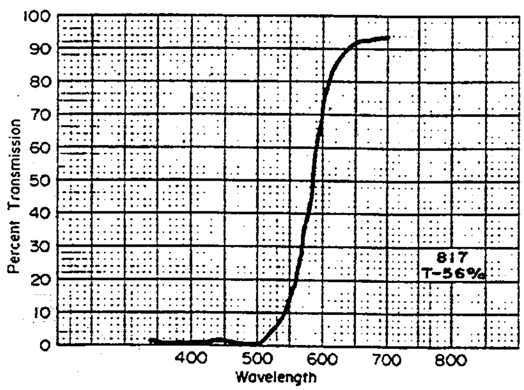
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Wavelength
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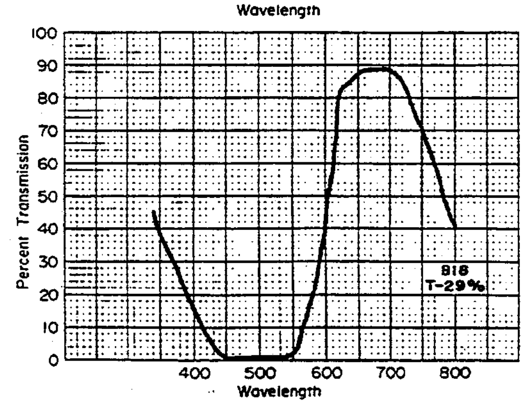
T-56%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Wavelength
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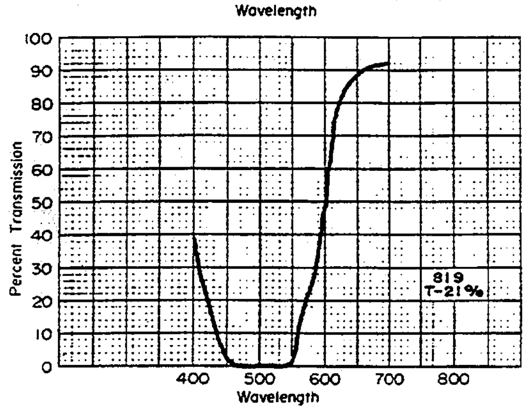
T-29%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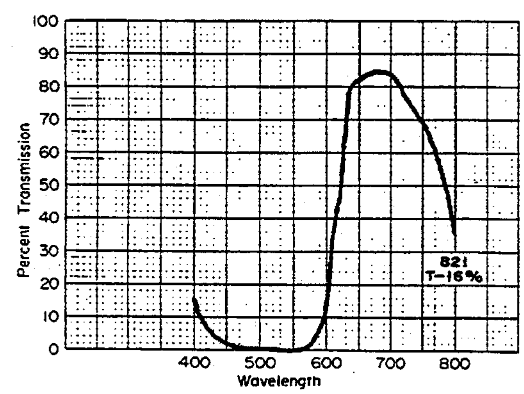
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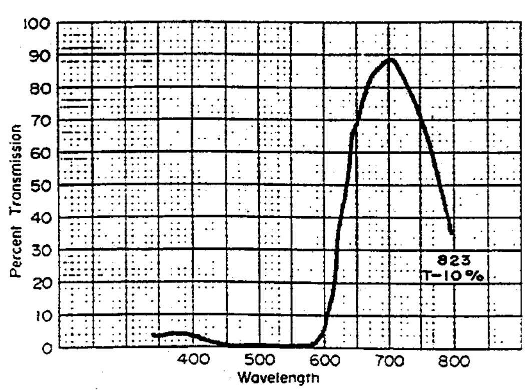
T-16%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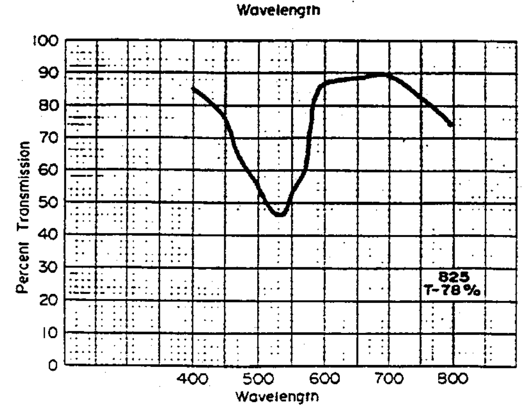
T-10%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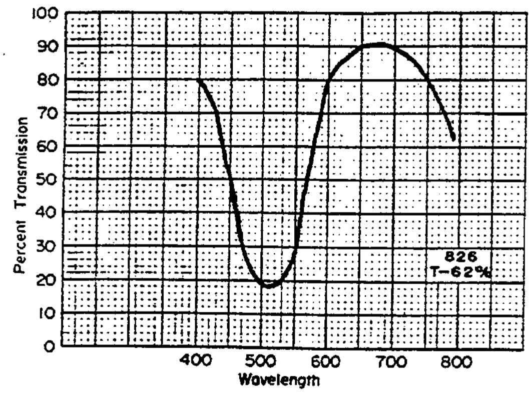
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Wavelength
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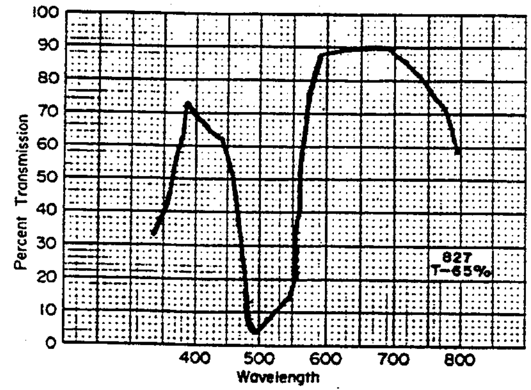
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Wavelength
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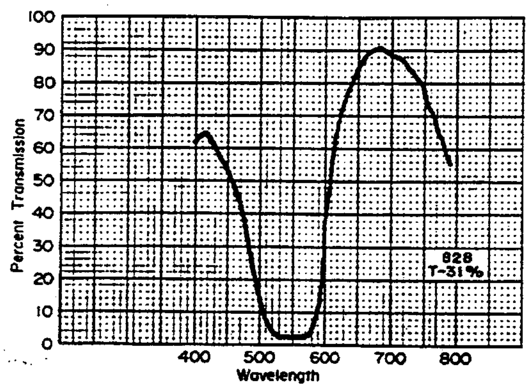
T-65%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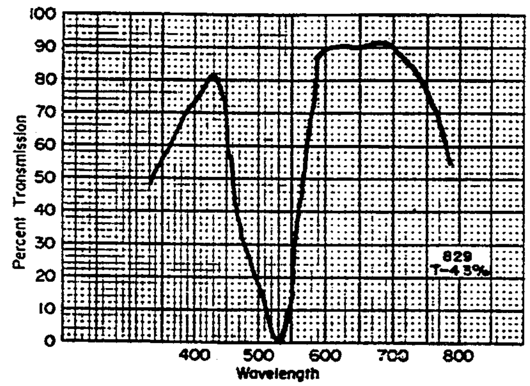
T-31%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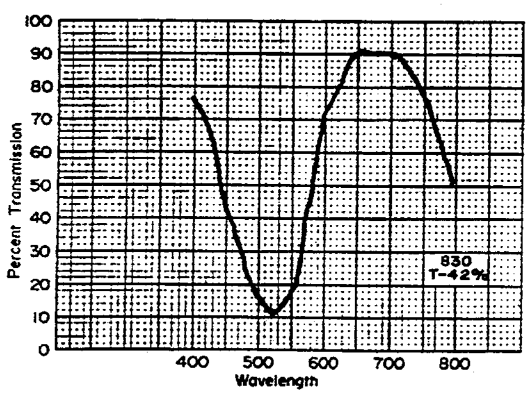
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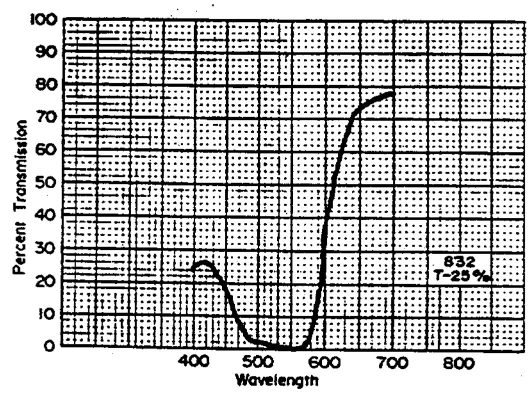
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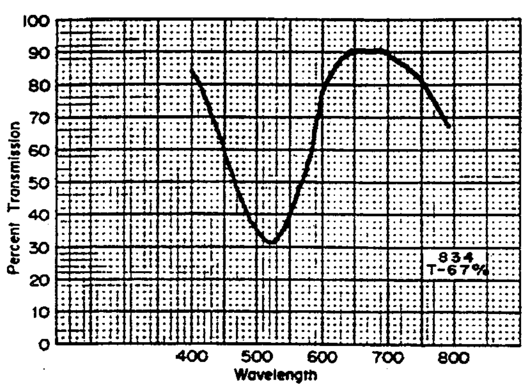
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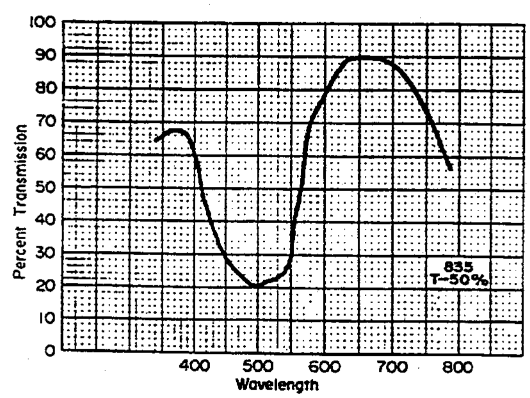
T-67%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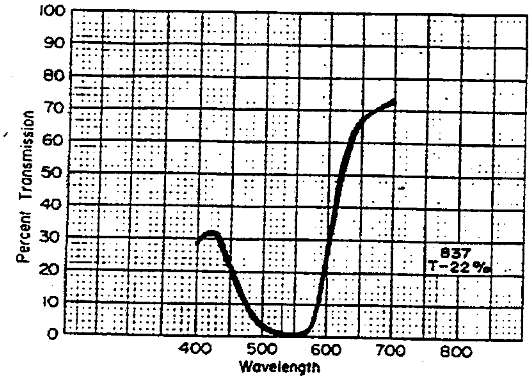
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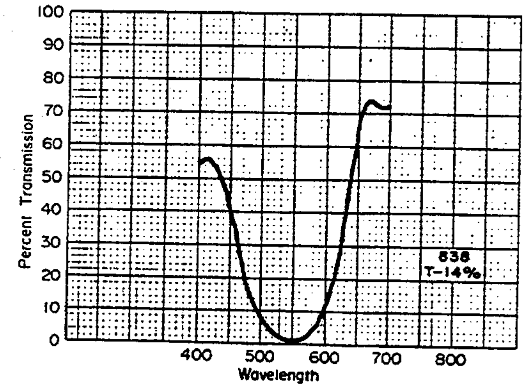
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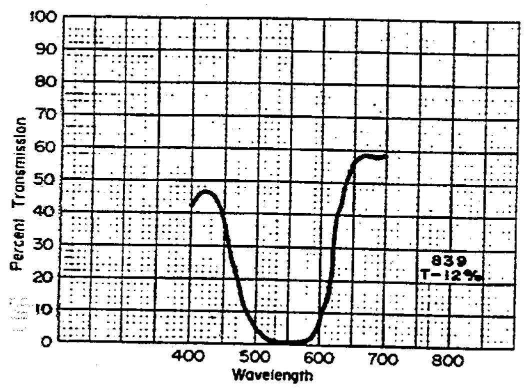
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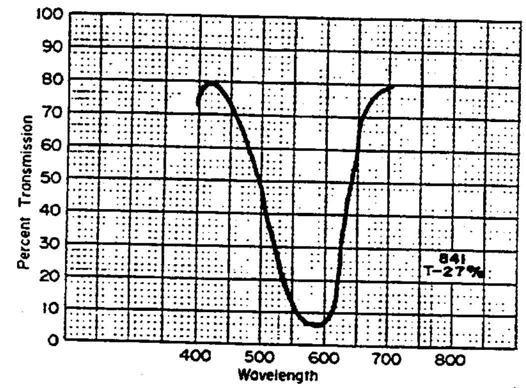
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Wavelength
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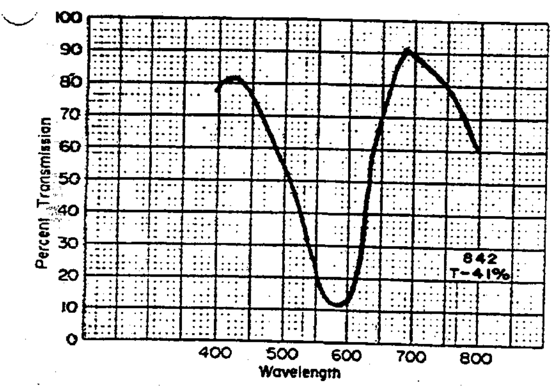
T-27%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Wavelength
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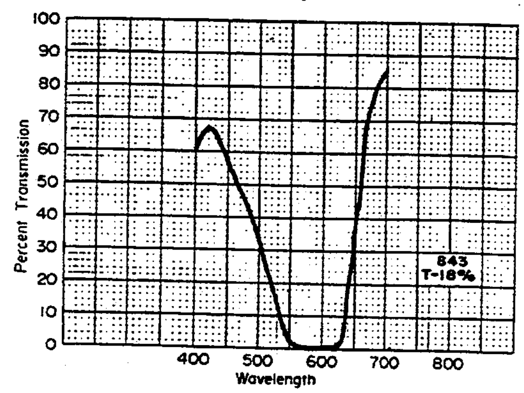
T-41%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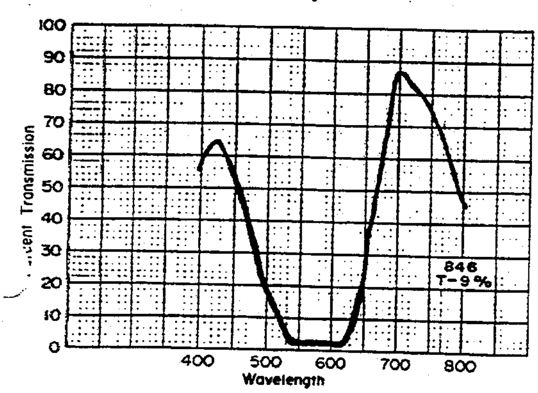
T-18%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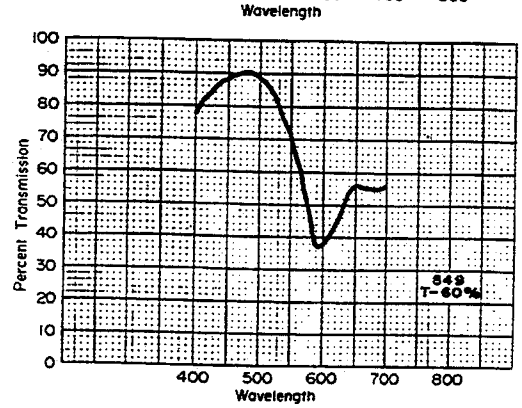
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Wavelength
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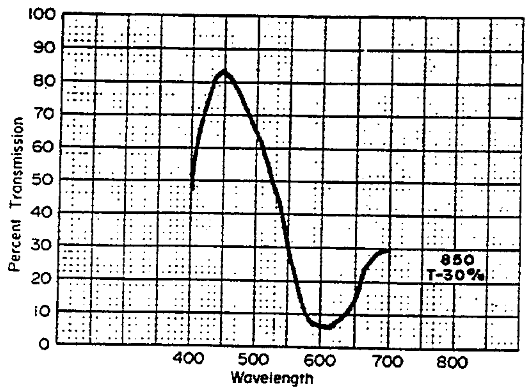
T-60%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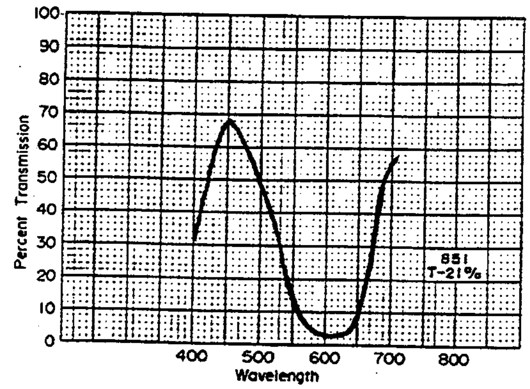
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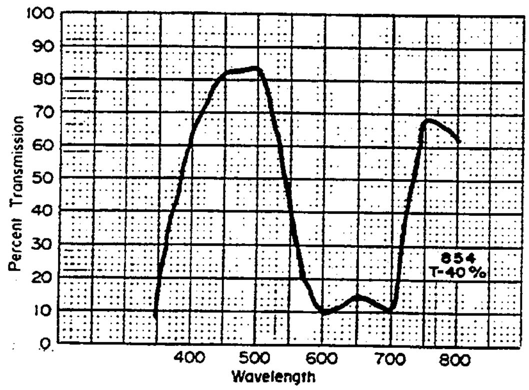
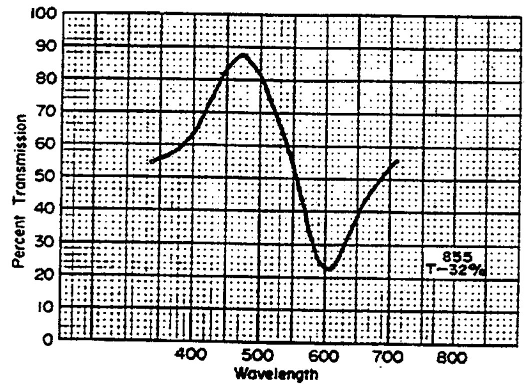
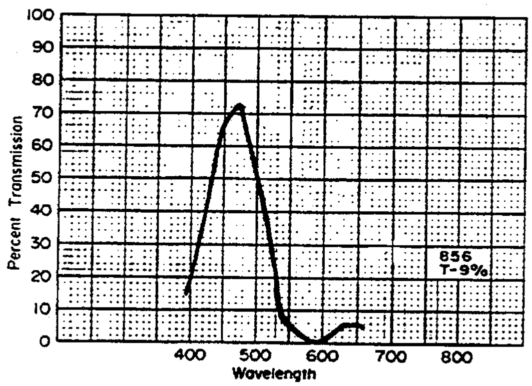
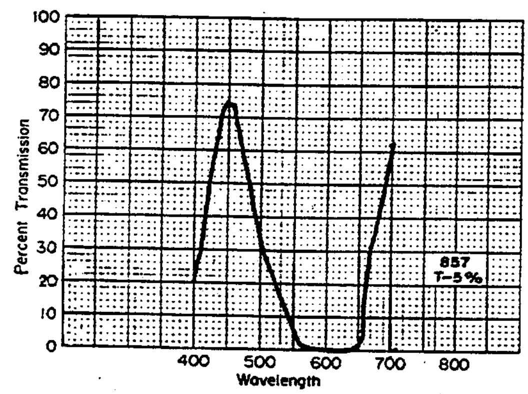
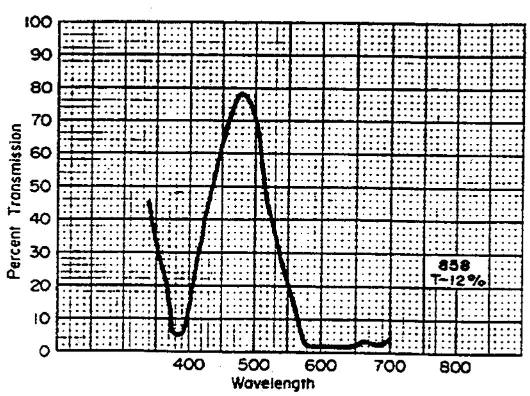
851
T-21%

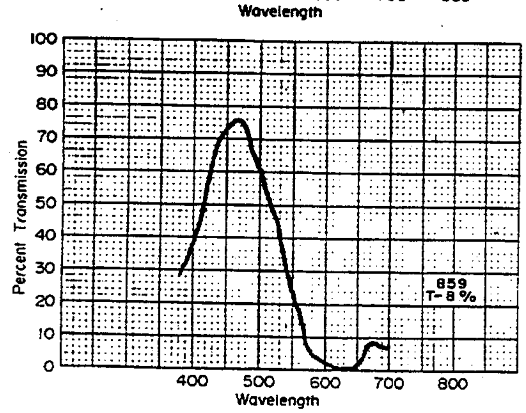

Percent Transmission
100 90 80 70 60 50 40 30 20 10 0
400 500 600 700 800
Wavelength
854
T-40%

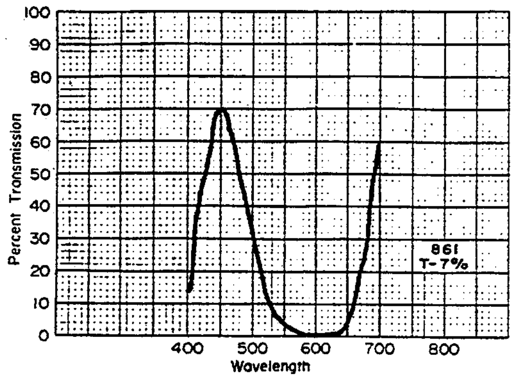

Percent Transmission
100 90 80 70 60 50 40 30 20 10 0
400 500 600 700 800
Wavelength
855
T-32%

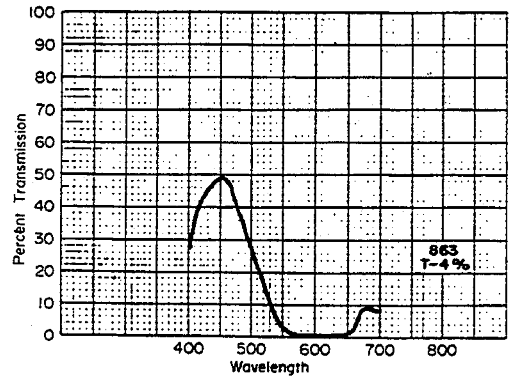

Percent Transmission
100 90 80 70 60 50 40 30 20 10 0
400 500 600 700 800
Wavelength
856
T-9%

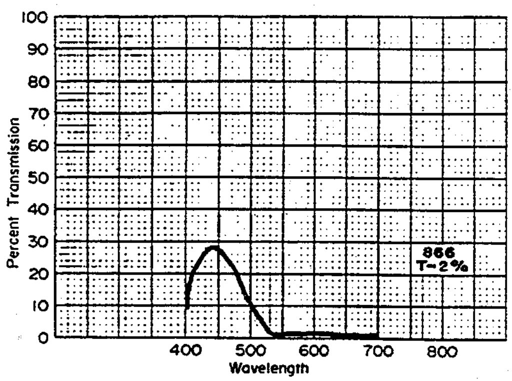

Percent Transmission
100 90 80 70 60 50 40 30 20 10 0
400 500 600 700 800
Wavelength
857
T-5%

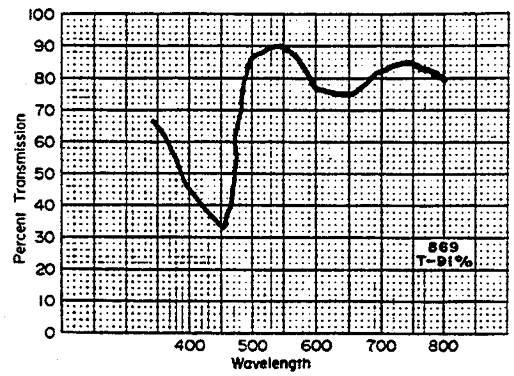

Percent Transmission
100 90 80 70 60 50 40 30 20 10 0
400 500 600 700 800
Wavelength
858
T-12%

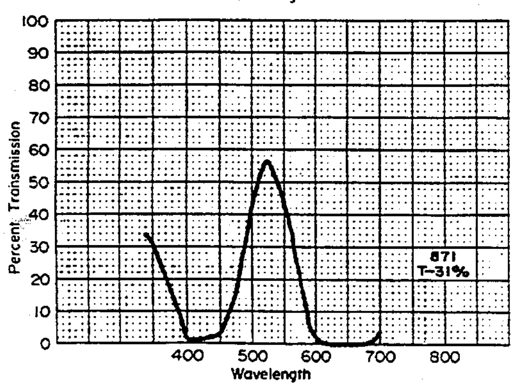

Percent Transmission
100 90 80 70 60 50 40 30 20 10 0
400 500 600 700 800
Wavelength
859
T-8%

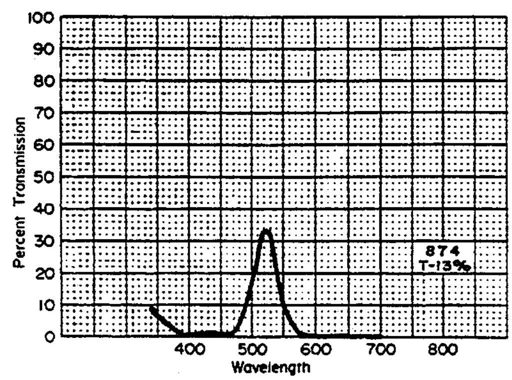

Percent Transmission
Wavelength
861
T-7%

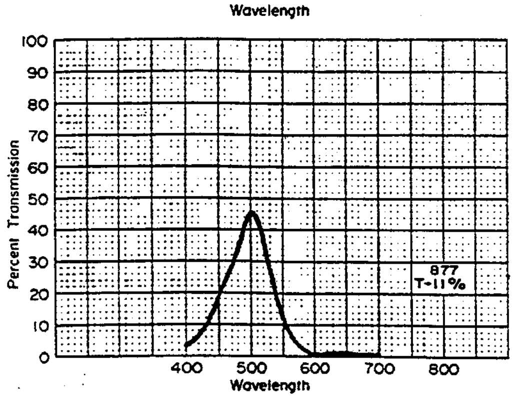

Percent Transmission
Wavelength
863
T-4%

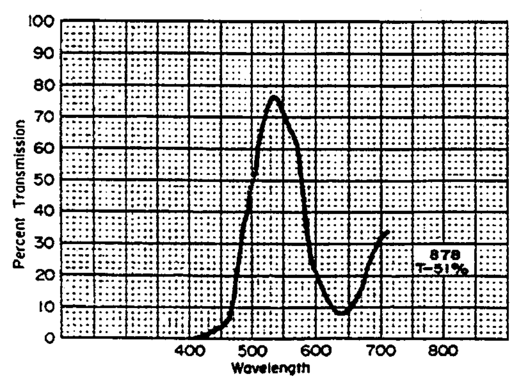

Percent Transmission
Wavelength
866
T-2%

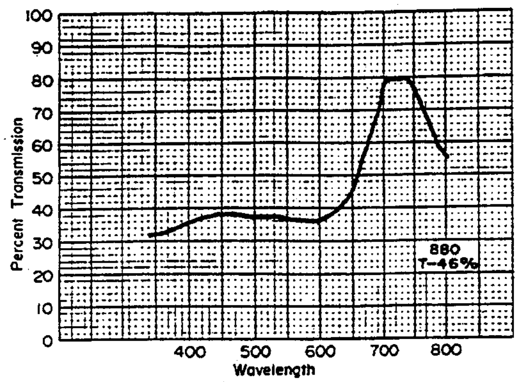

Percent Transmission
Wavelength
869
T-91%

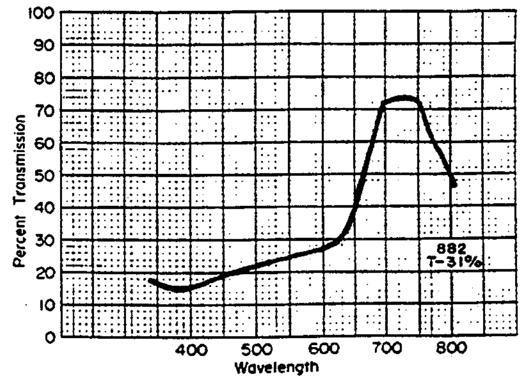

Percent Transmission
Wavelength
871
T-31%

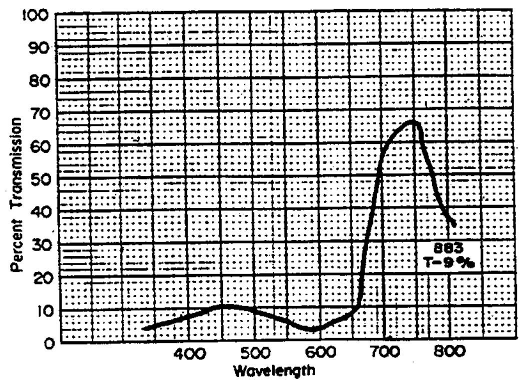

Percent Transmission
Wavelength
874
T-13%


Percent Transmission
Wavelength
877
T-11%

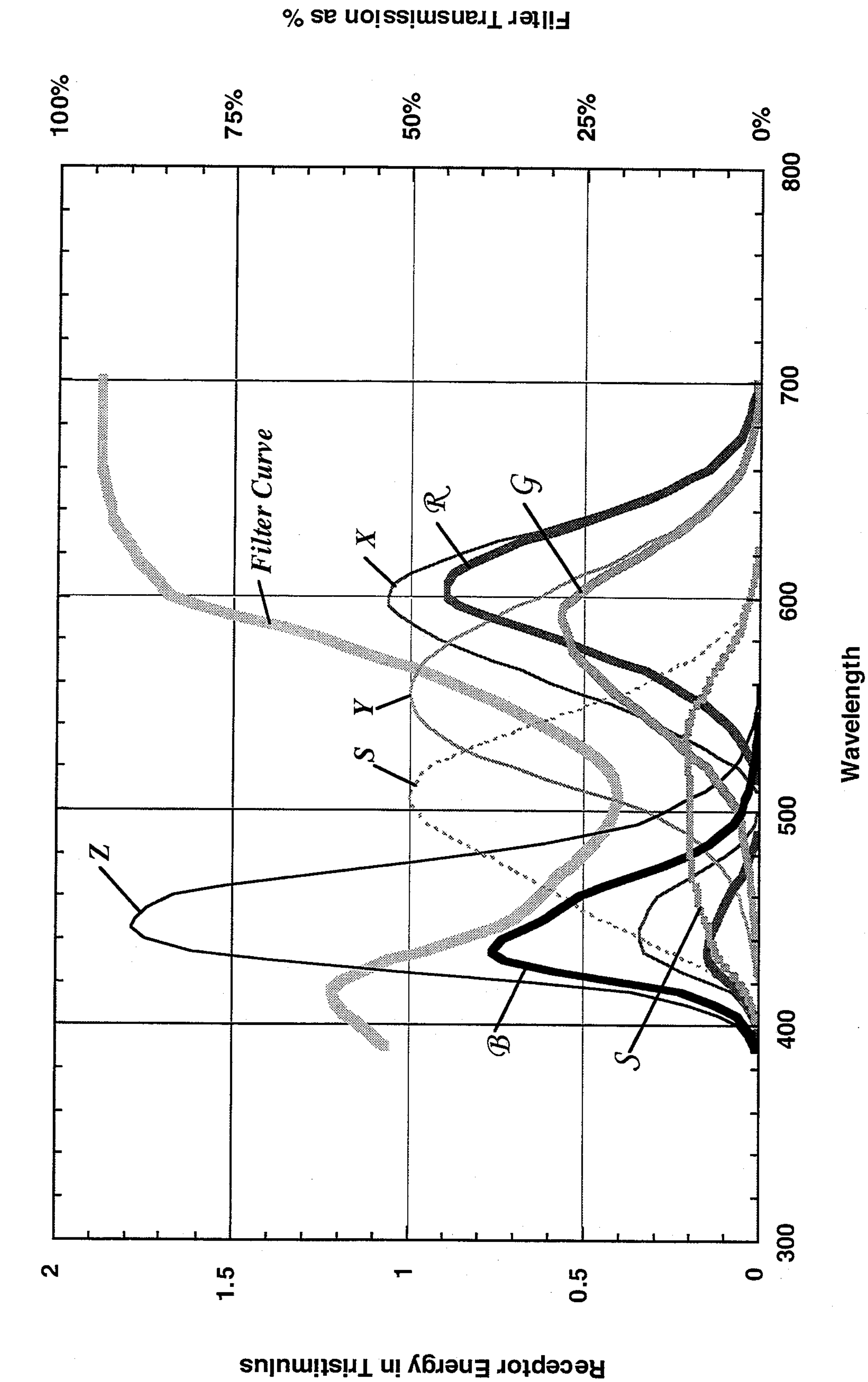

Percent Transmission
Wavelength
878
T-51%


Percent Transmission
100
90
80
70
60
50
40
30
20
10
0
400
500
600
700
800
Wavelength
880
T-46%

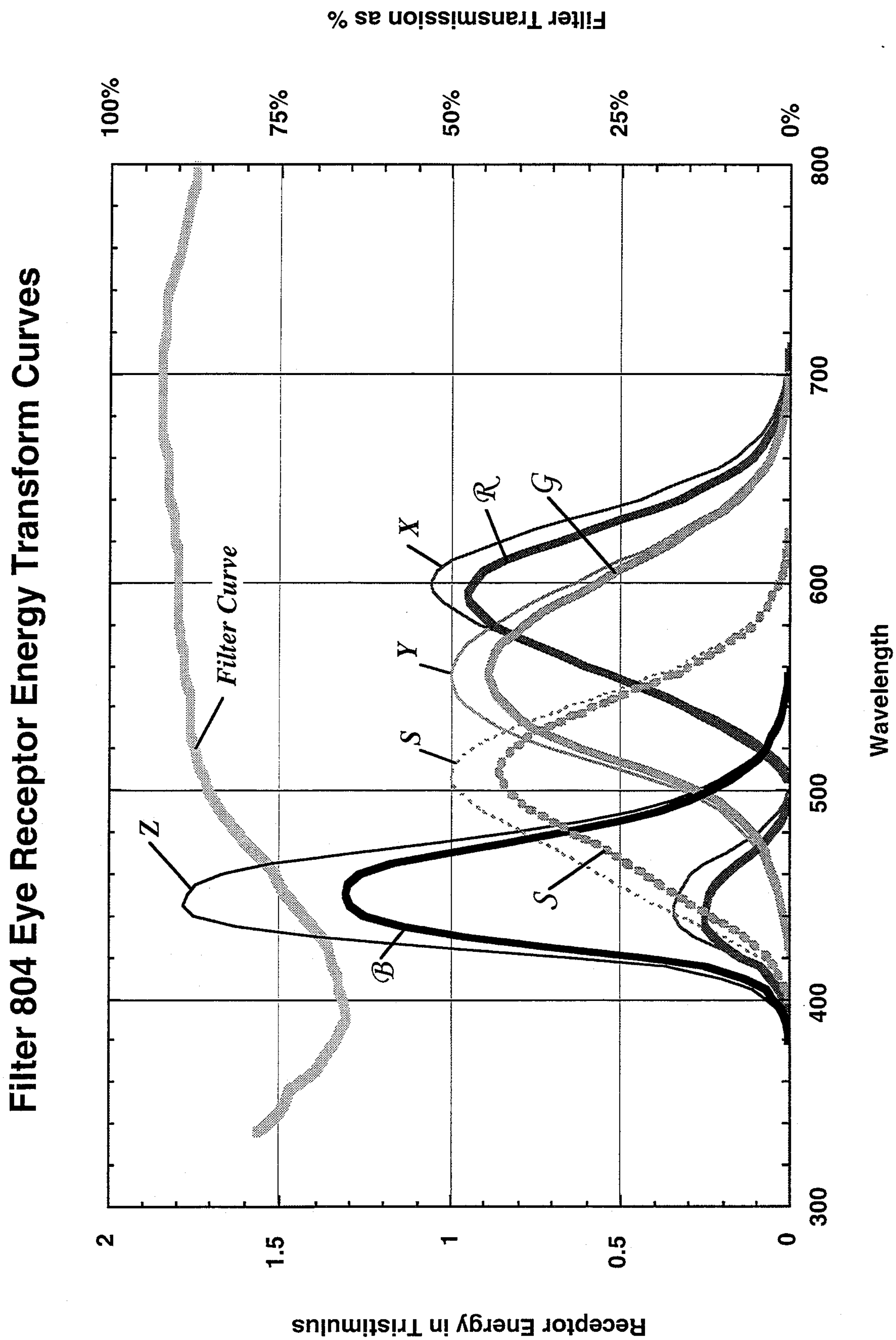

Percent Transmission
100
90
80
70
60
50
40
30
20
10
0
400
500
600
700
800
Wavelength
882
T-31%


Percent Transmission
100
90
80
70
60
50
40
30
20
10
0
400
500
600
700
800
Wavelength
883
T-9%

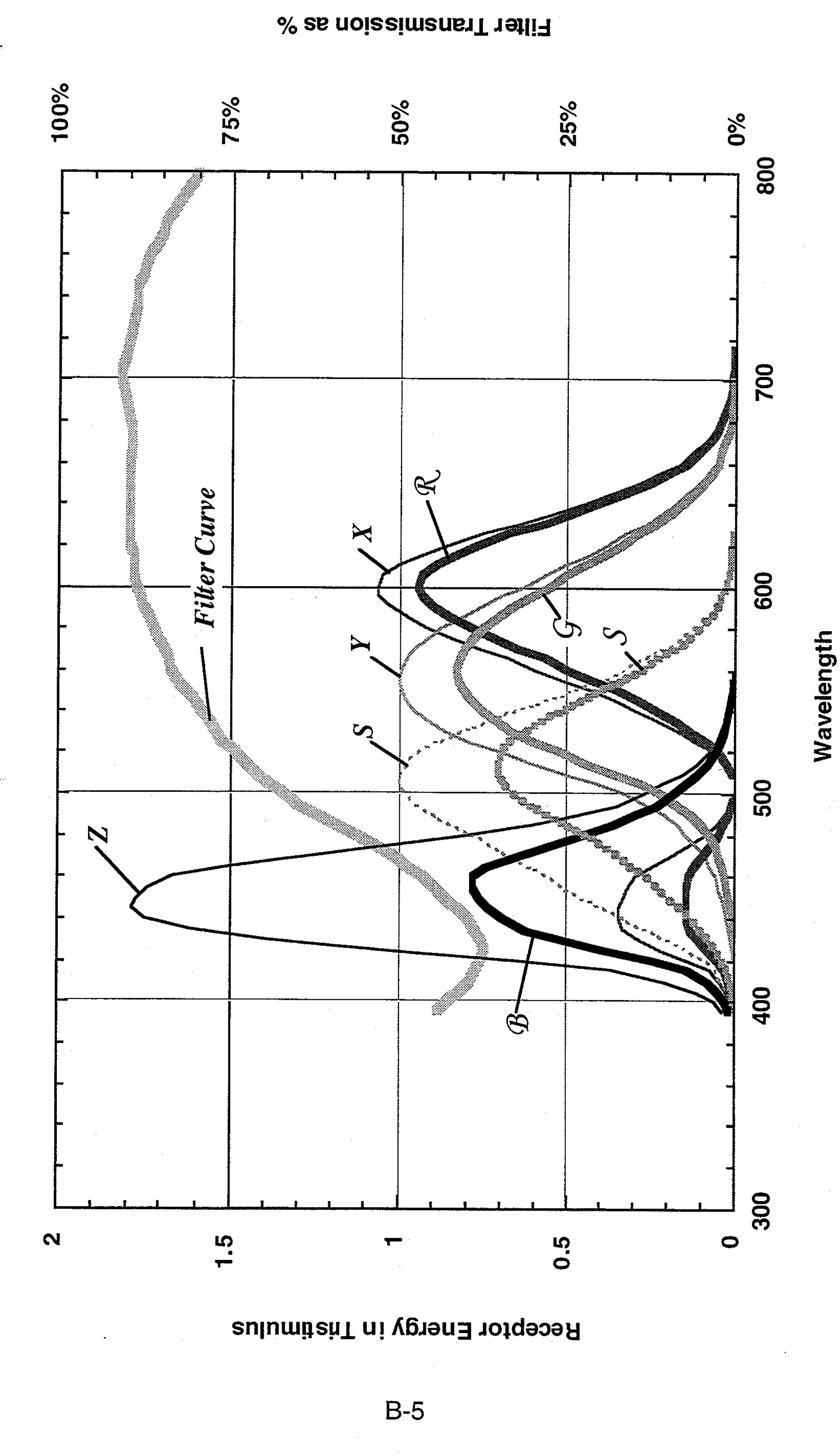
Appendix B
EYE TRANSFORMATIONS FOR FILTERS

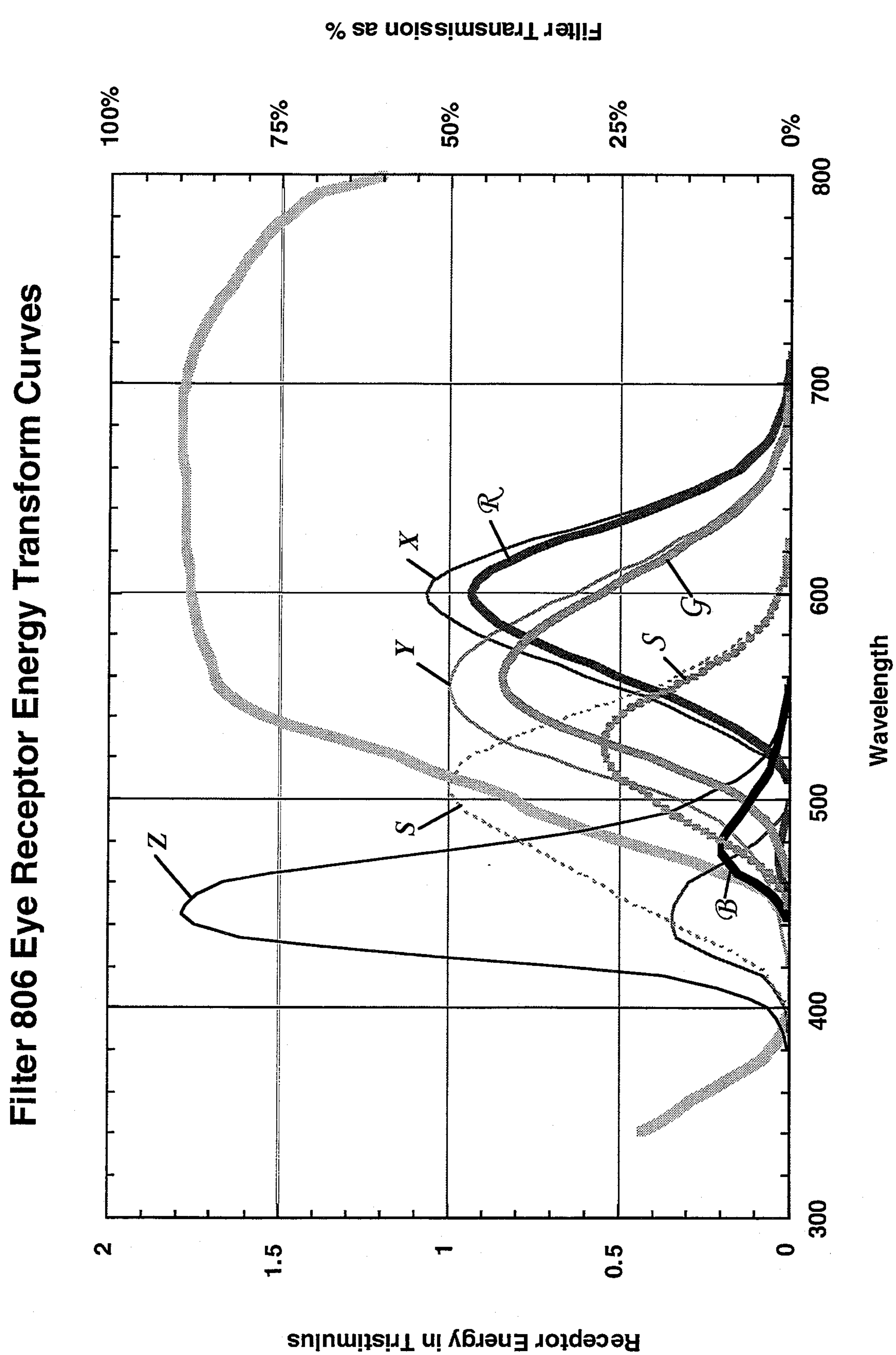


Filter 802 Eye Receptor Energy Transform Curves

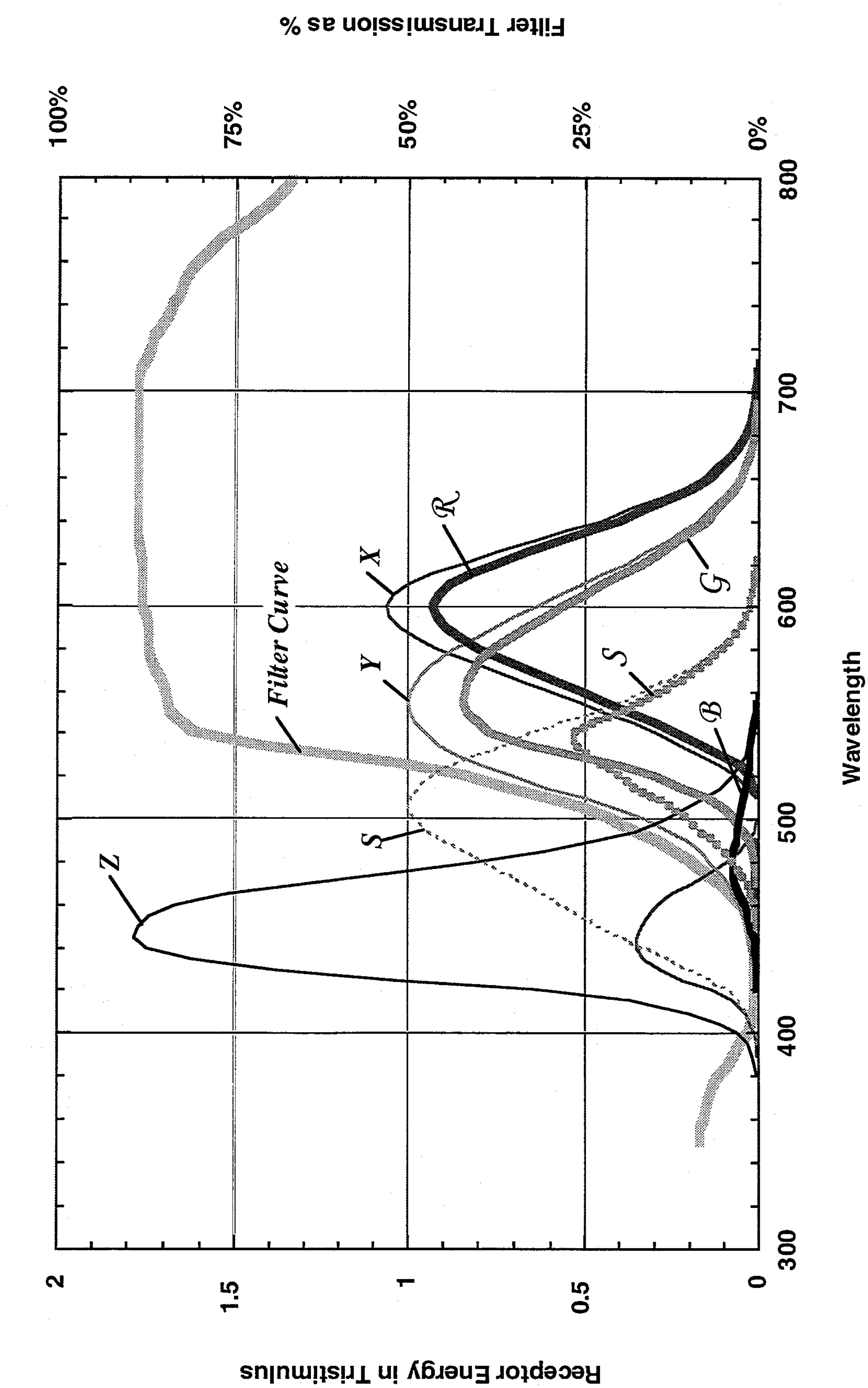

Filter 804 Eye Receptor Energy Transform Curves
Filter Transmission as %
100%
75%
50%
25%
0%
Receptor Energy in Tristimulus
2
1.5
1
0.5
0
Wavelength
300
400
500
600
700
800
Z
X
Y
S
S
R
G
B
Filter Curve

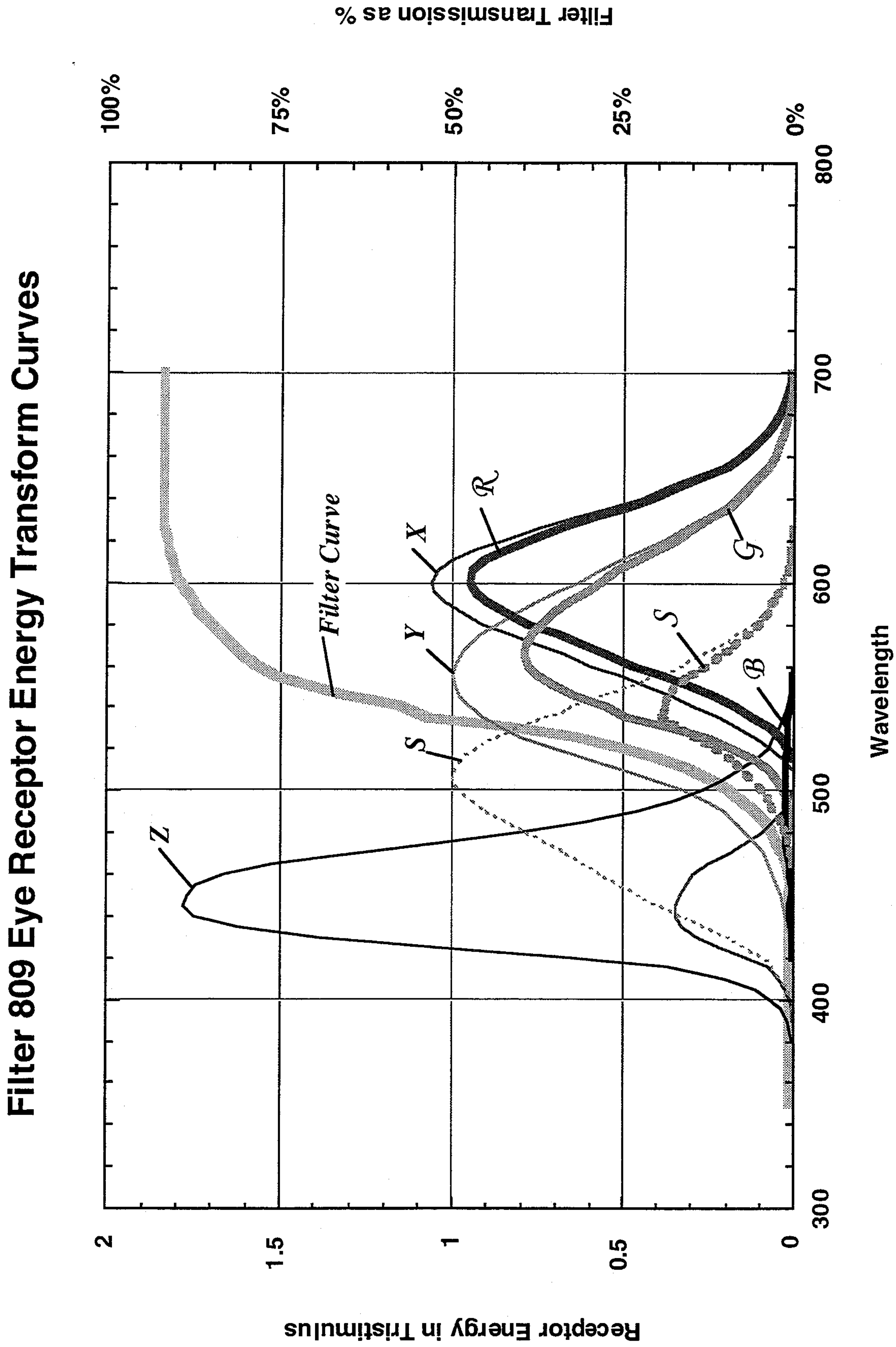
Filter 805 Eye Receptor Energy Transform Curves



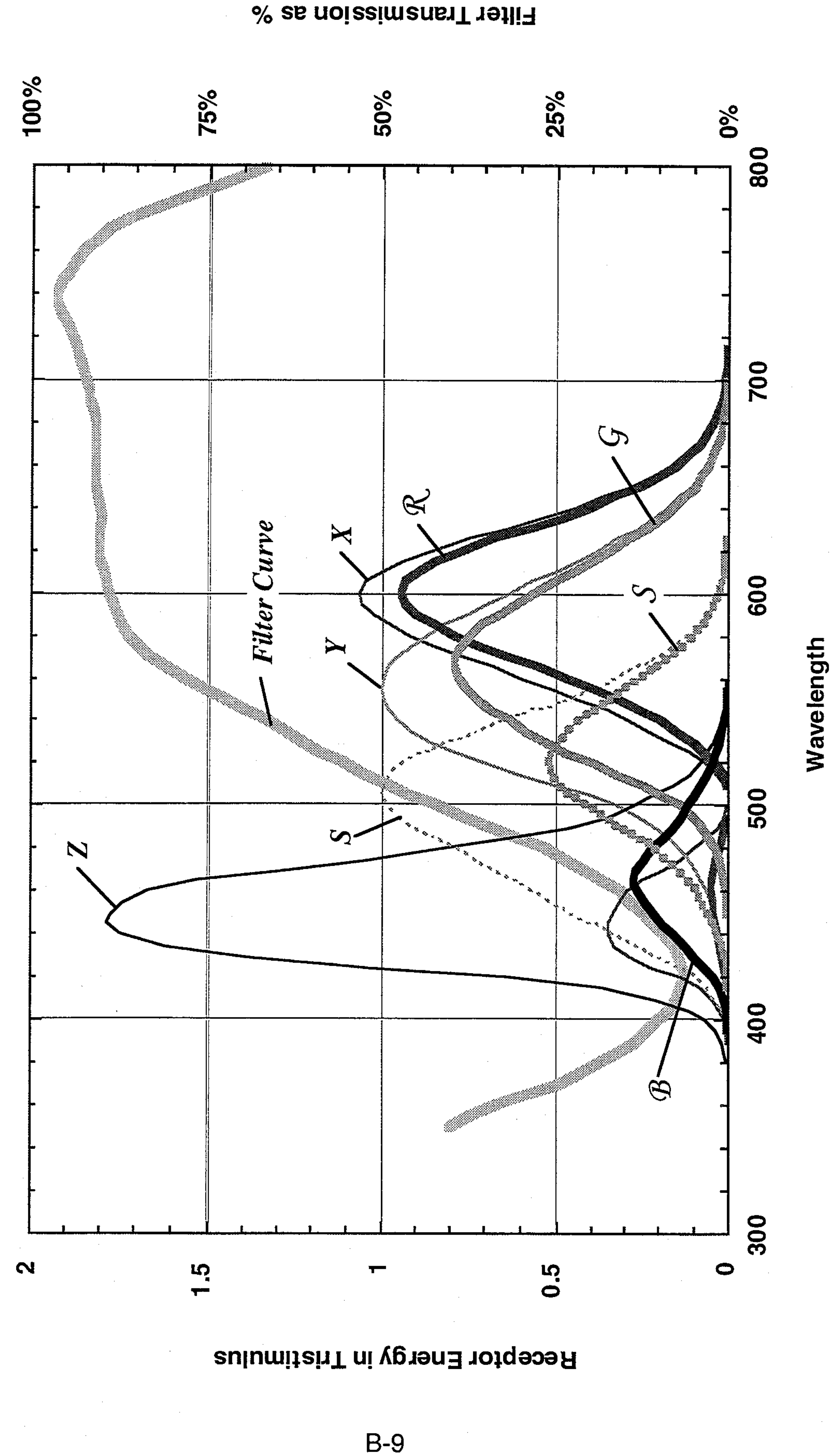

Filter 806 Eye Receptor Energy Transform Curves
Filter Transmission as %
100%
75%
50%
25%
0%
Receptor Energy in Tristimulus
2
1.5
1
0.5
0
300
400
500
600
700
800
Wavelength
Z
S
Y
X
R
S
G
B

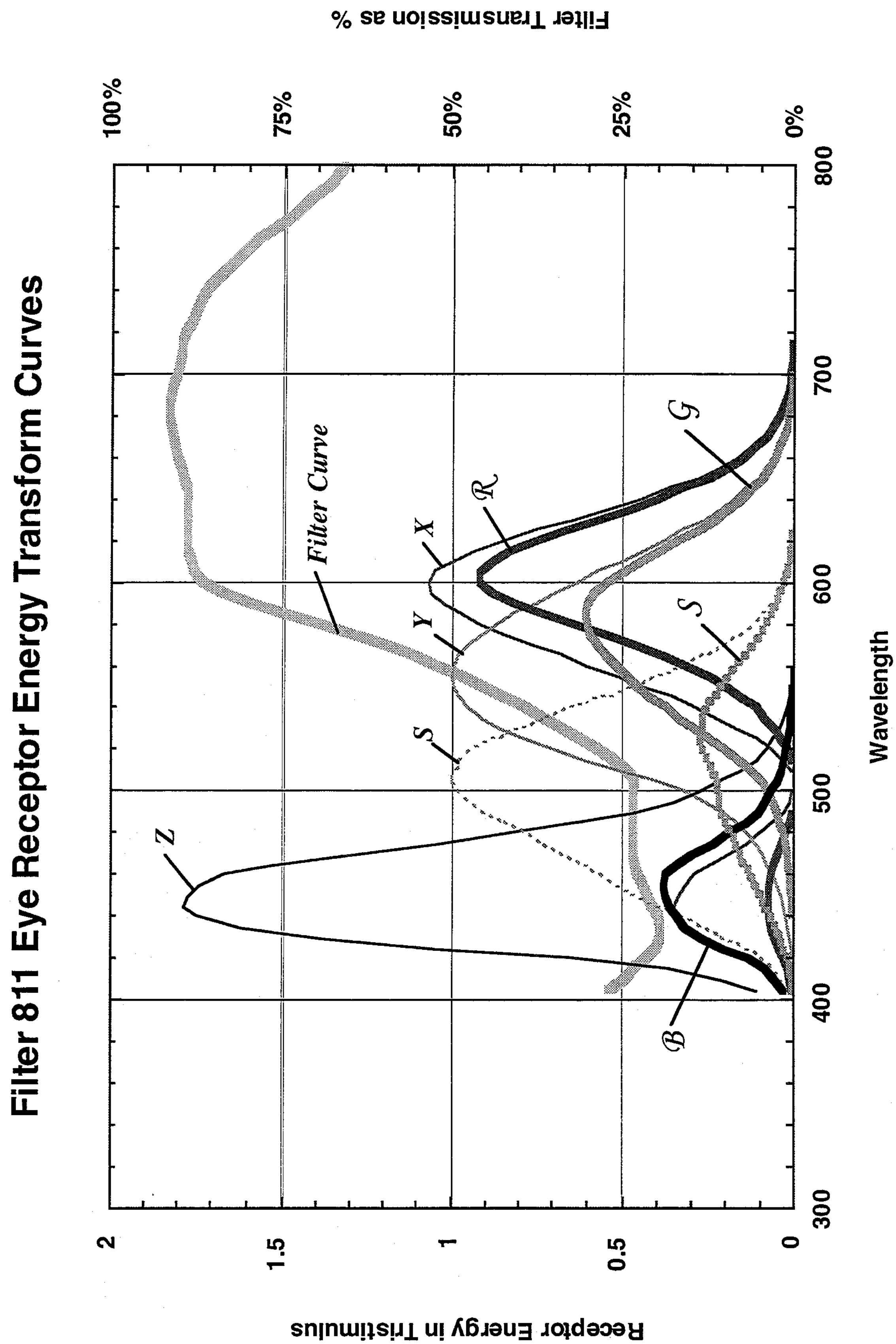
Filter 807 Eye Receptor Energy Transform Curves



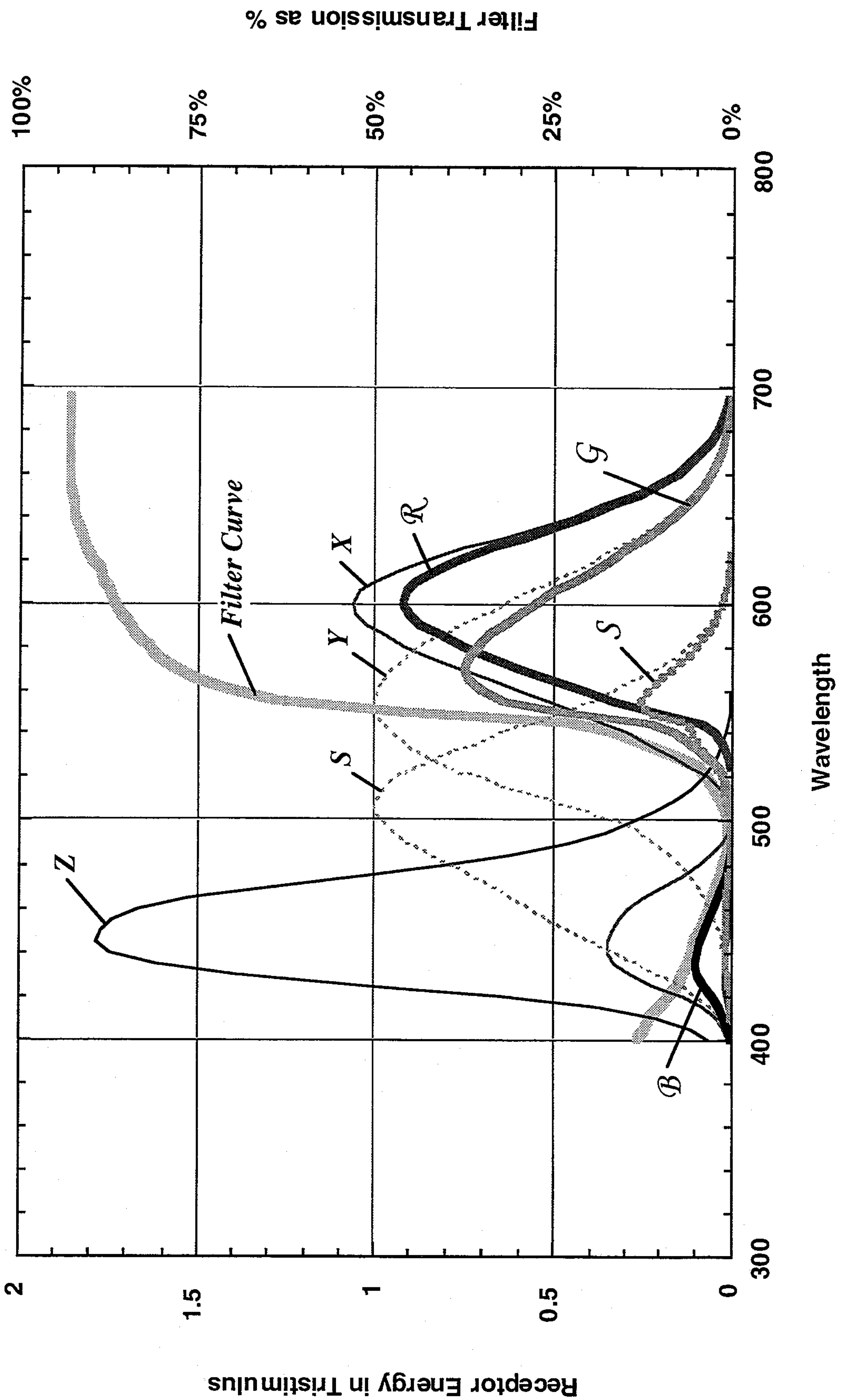

Filter 809 Eye Receptor Energy Transform Curves
Filter Transmission as %
100%
75%
50%
25%
0%
Receptor Energy in Tristimulus
2
1.5
1
0.5
0
300
400
500
600
700
800
Wavelength
Z
S
Y
X
Filter Curve
R
S
B
G

Filter 810 Eye Receptor Energy Transform Curves

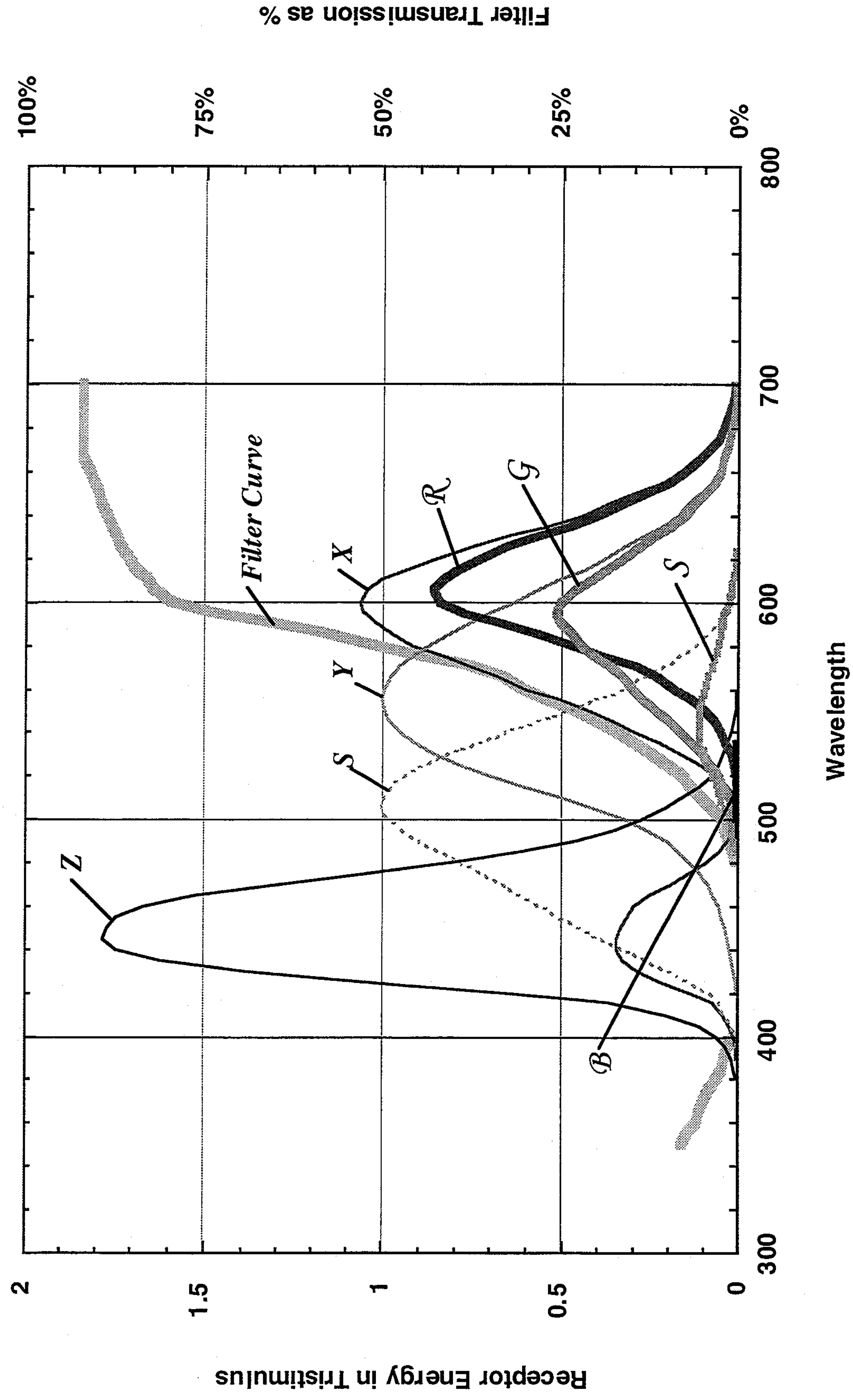


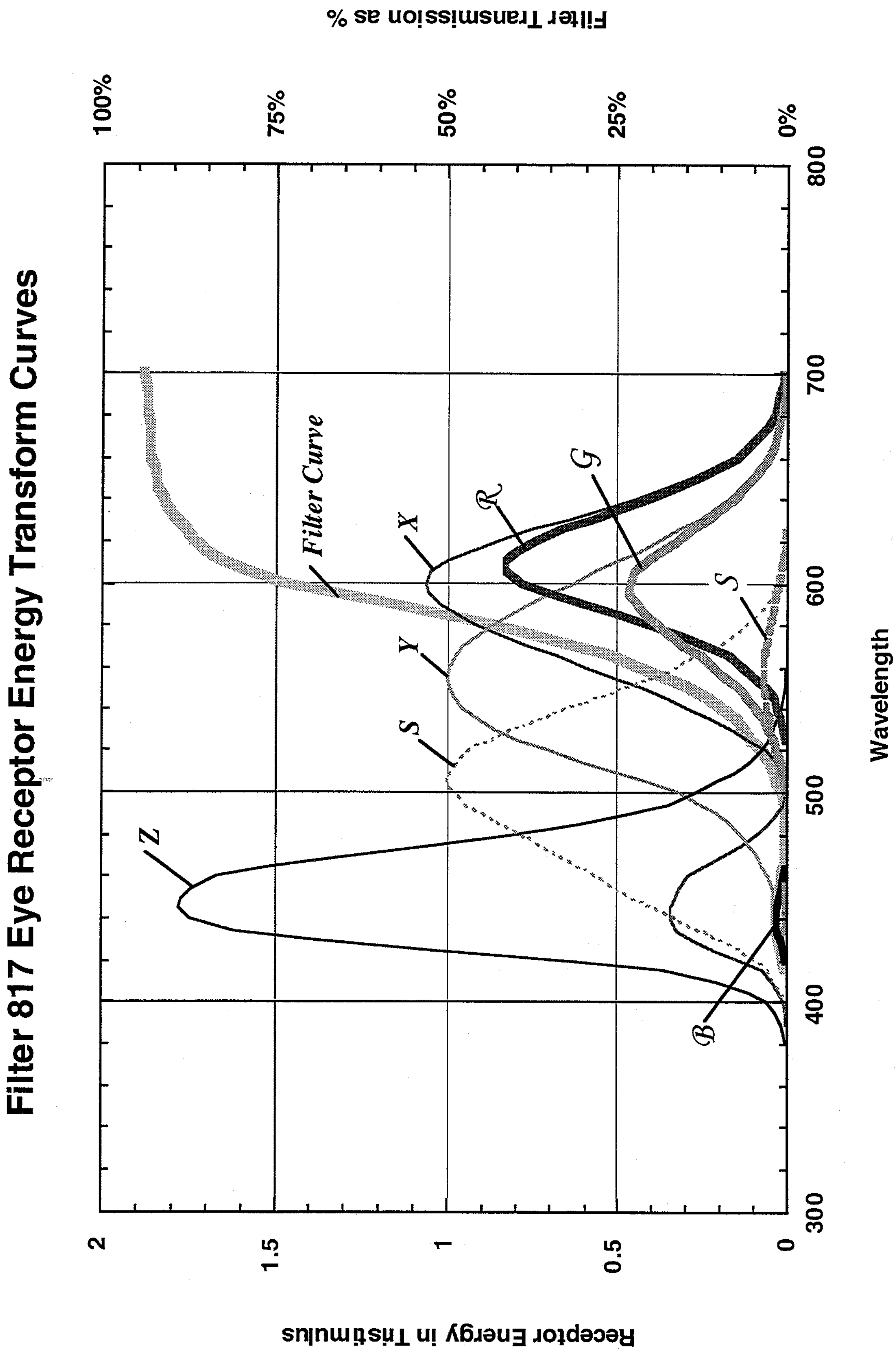

Filter 811 Eye Receptor Energy Transform Curves
Filter Transmission as %
100%
75%
50%
25%
0%
Receptor Energy in Tristimulus
2
1.5
1
0.5
0
300
400
500
600
700
800
Wavelength
Filter Curve
Z
X
Y
S
S
R
G
B

Filter 813 Eye Receptor Energy Transform Curves

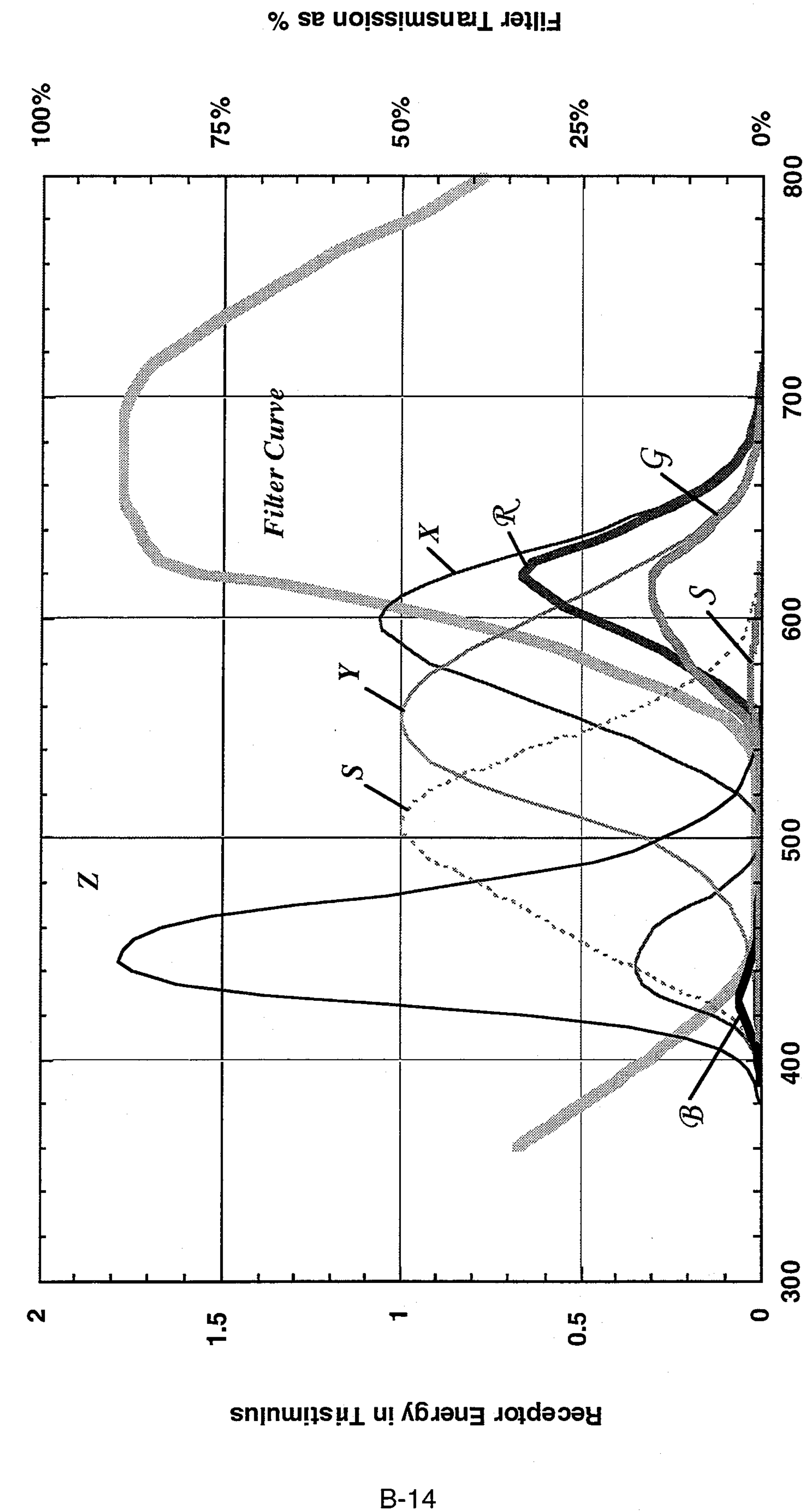


Filter 815 Eye Receptor Energy Transform Curves

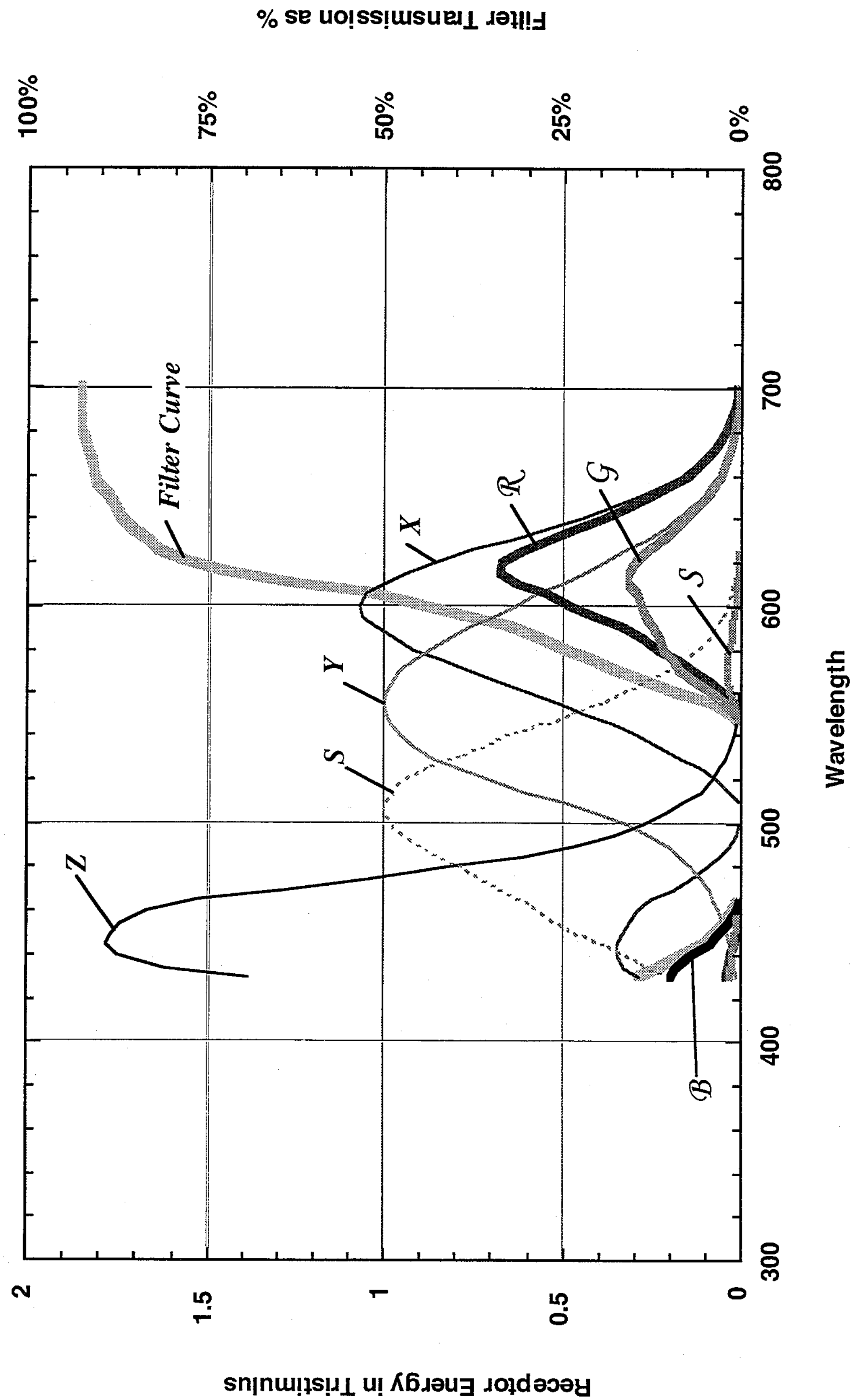


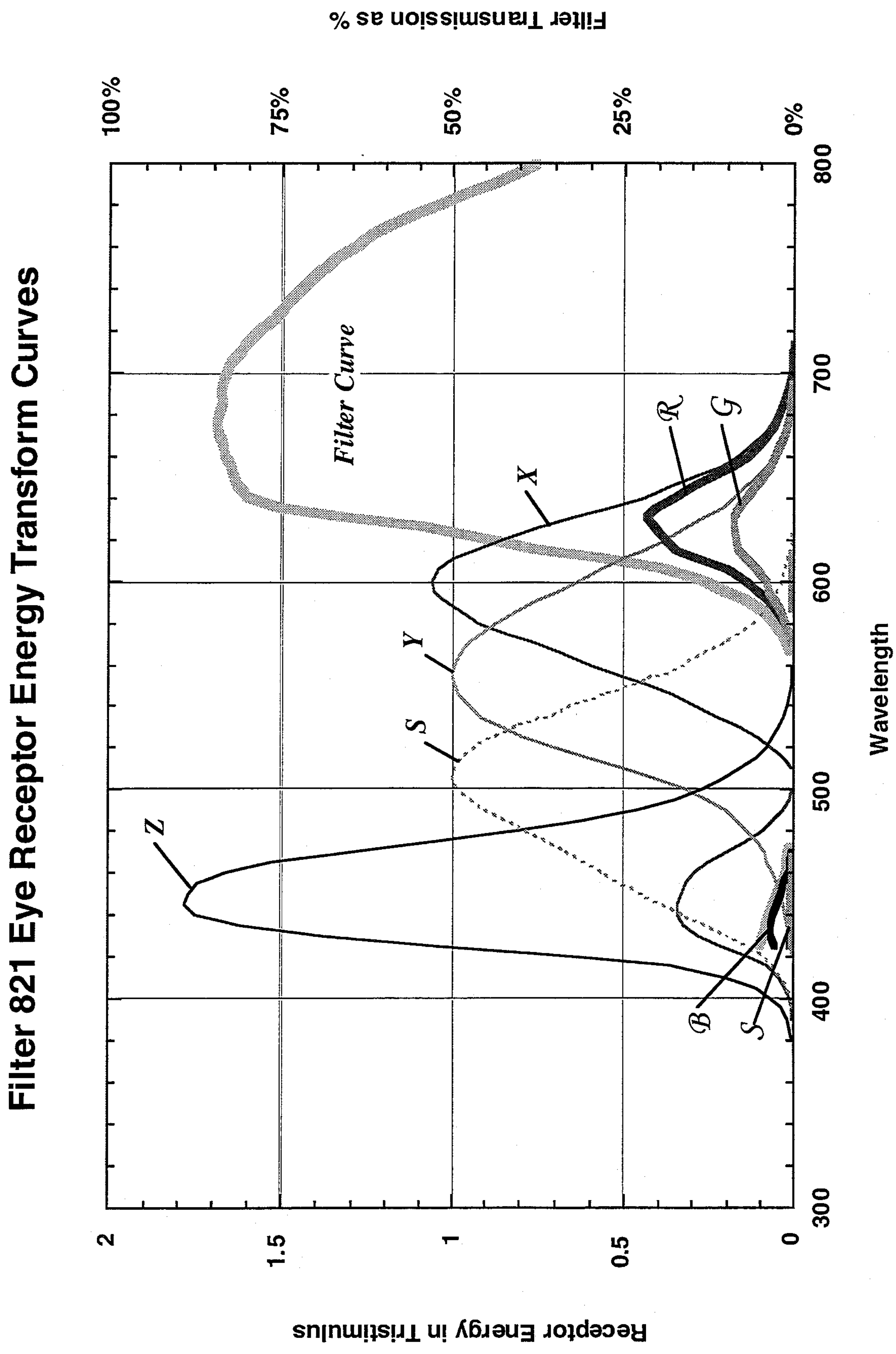

Filter 817 Eye Receptor Energy Transform Curves
Filter Transmission as %
100%
75%
50%
25%
0%
Receptor Energy in Tristimulus
2
1.5
1
0.5
0
Wavelength
300
400
500
600
700
800
Z
S
Y
X
R
G
S
B
Filter Curve

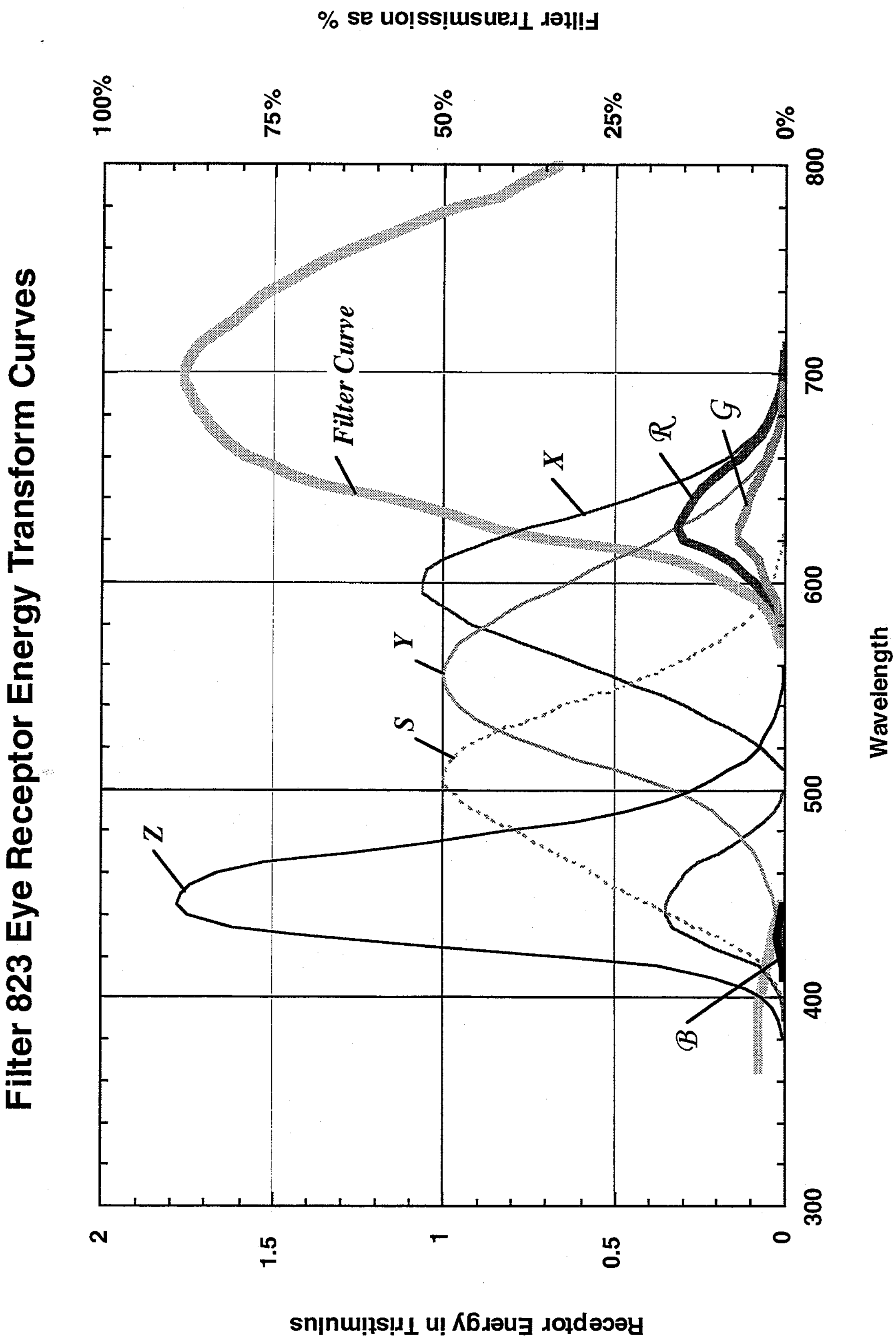
Filter 818 Eye Receptor Energy Transform Curves

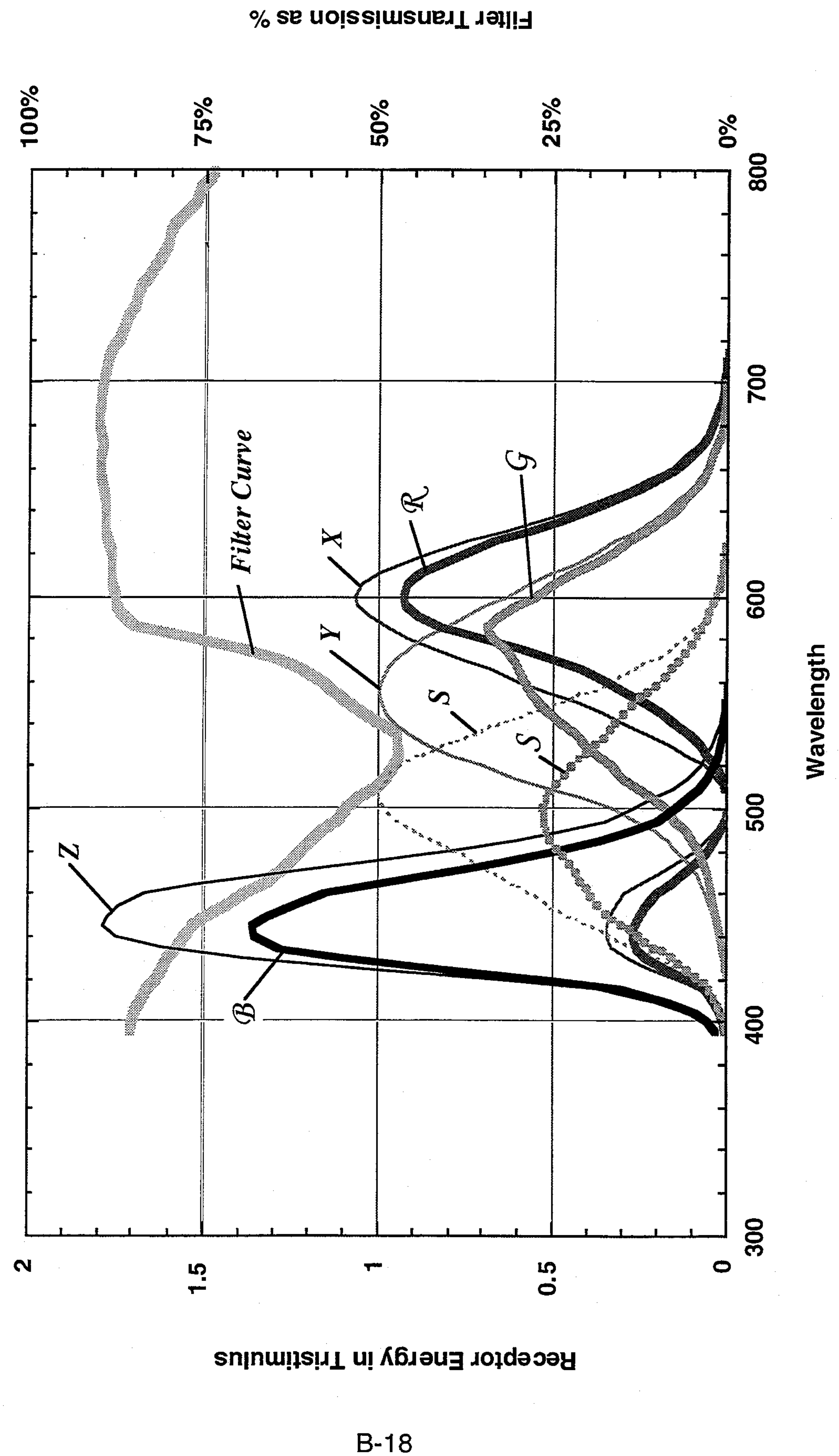


Filter 819 Eye Receptor Energy Transform Curves

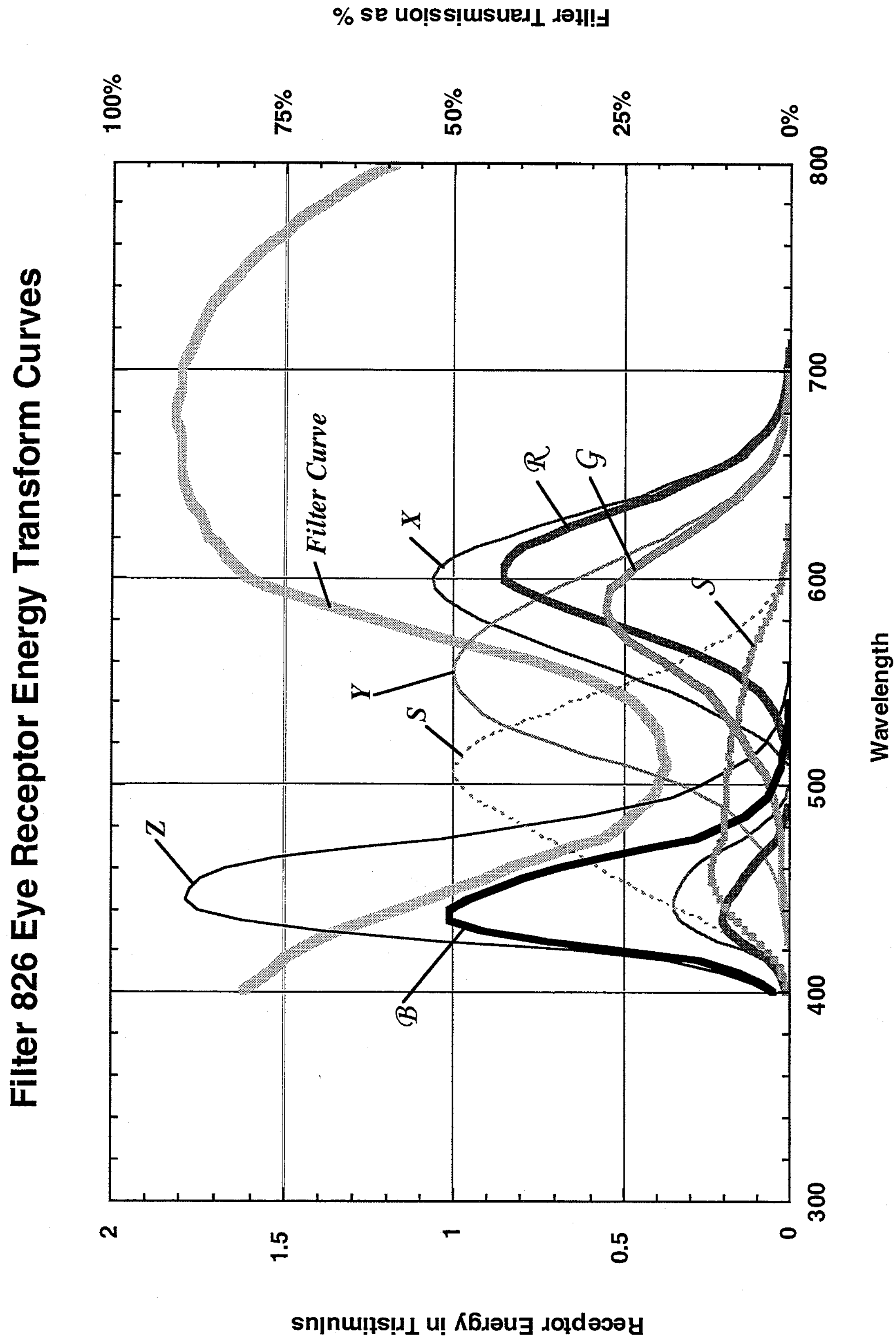



Filter 821 Eye Receptor Energy Transform Curves
Filter Transmission as %
100%
75%
50%
25%
0%
Receptor Energy in Tristimulus
2
1.5
1
0.5
0
300
400
500
600
700
800
Wavelength
Z
S
Y
X
Filter Curve
R
G
B
S

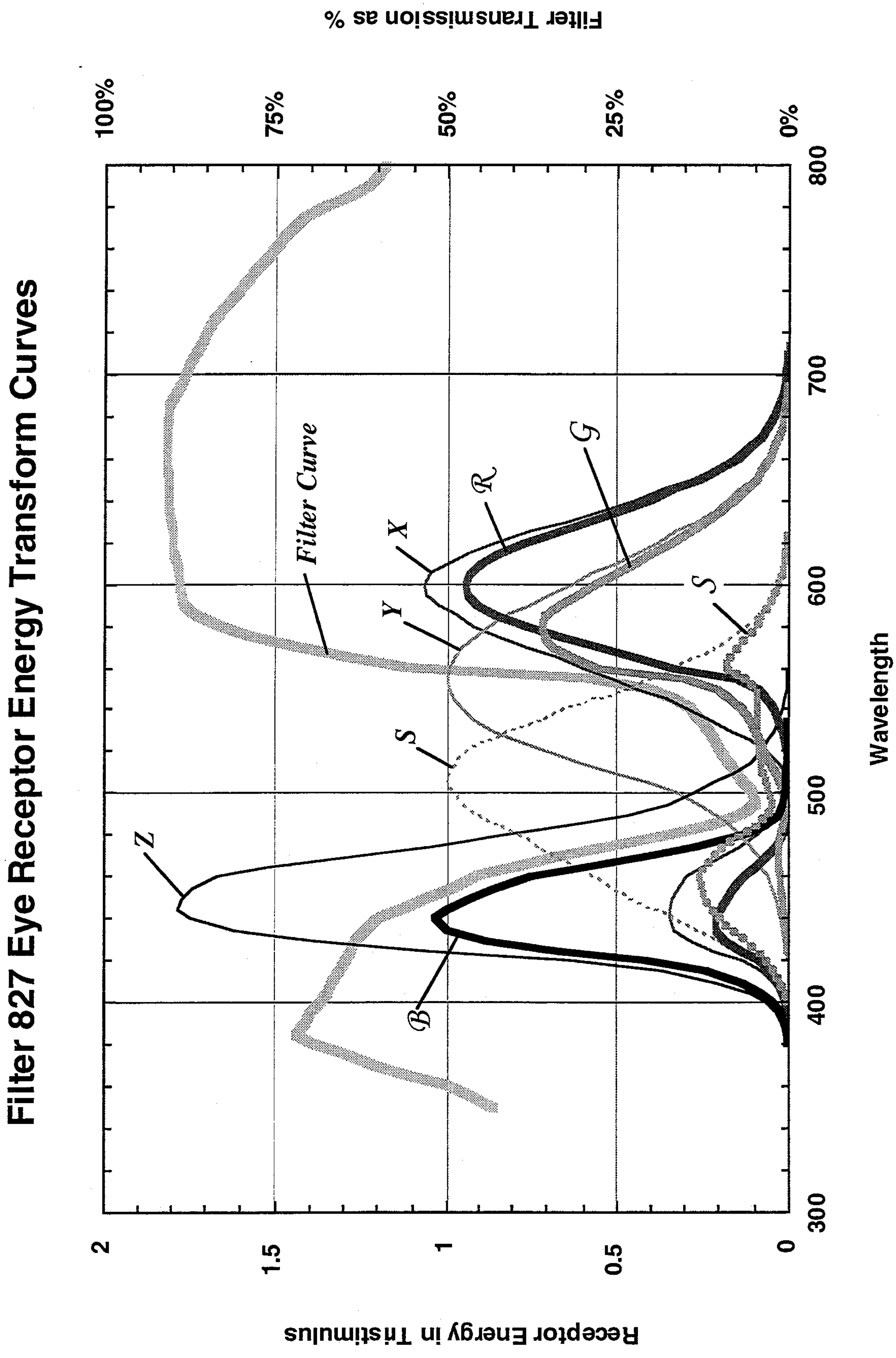

Filter 823 Eye Receptor Energy Transform Curves
Filter Transmission as %
100%
75%
50%
25%
0%
Receptor Energy in Tristimulus
2
1.5
1
0.5
0
Wavelength
300
400
500
600
700
800
Filter Curve
X
Y
Z
S
R
G
B



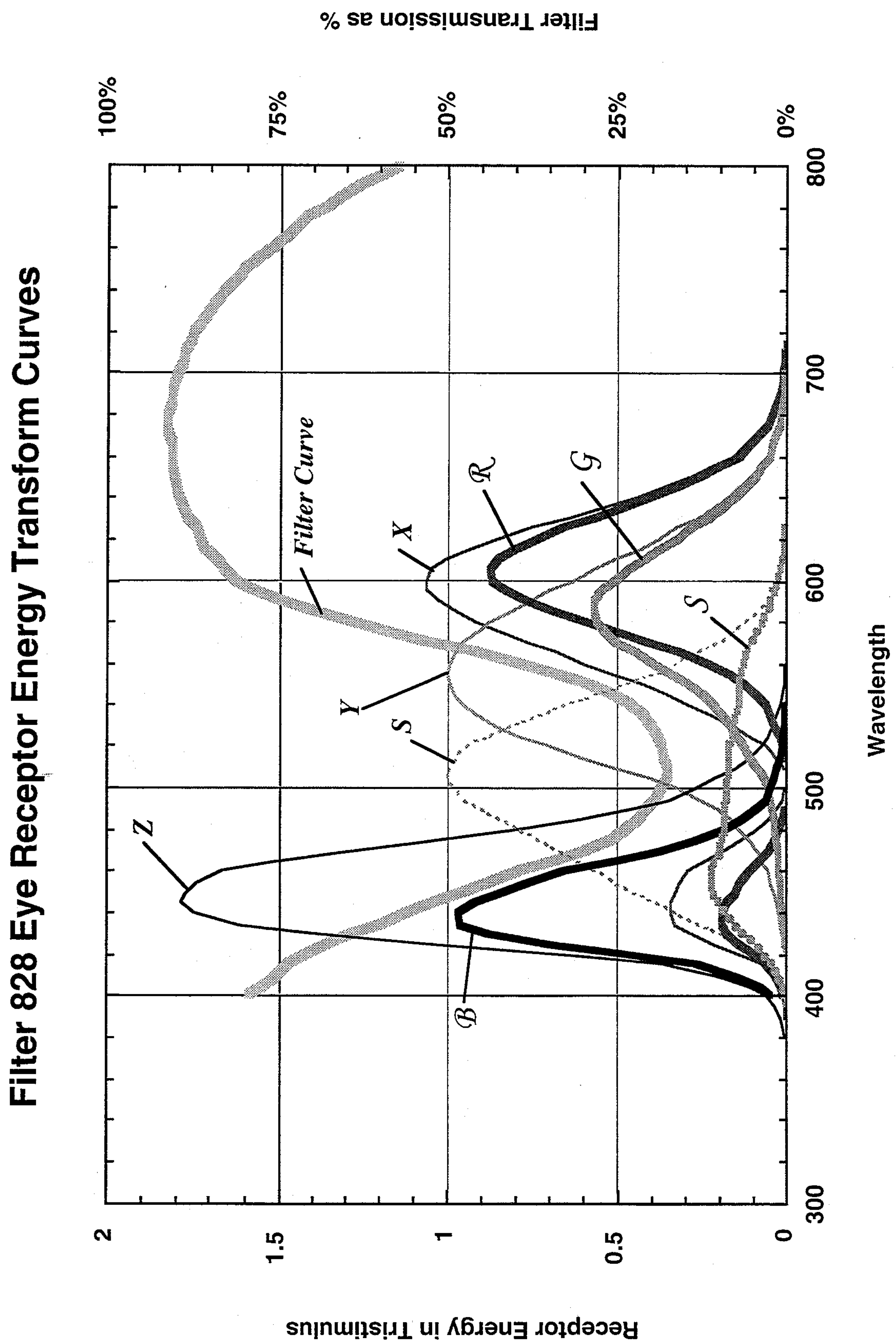
Filter 825 Eye Receptor Energy Transform Curves



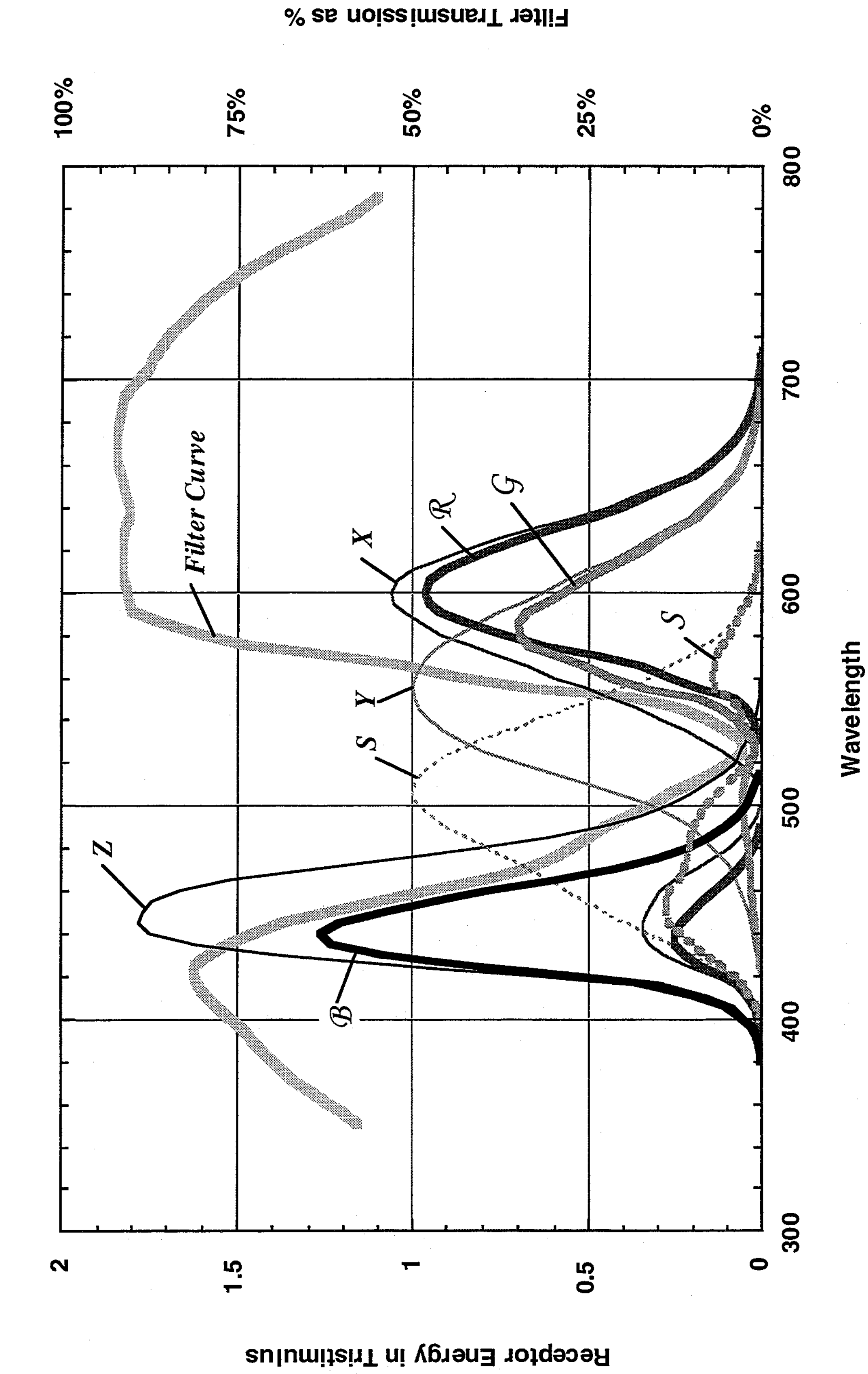
Filter 826 Eye Receptor Energy Transform Curves
Filter Transmission as %
100%
75%
50%
25%
0%
Receptor Energy in Tristimulus
2
1.5
1
0.5
0
300
400
500
600
700
800
Wavelength
Filter Curve
X
Y
Z
S
S
ℛ
𝒢
ℬ



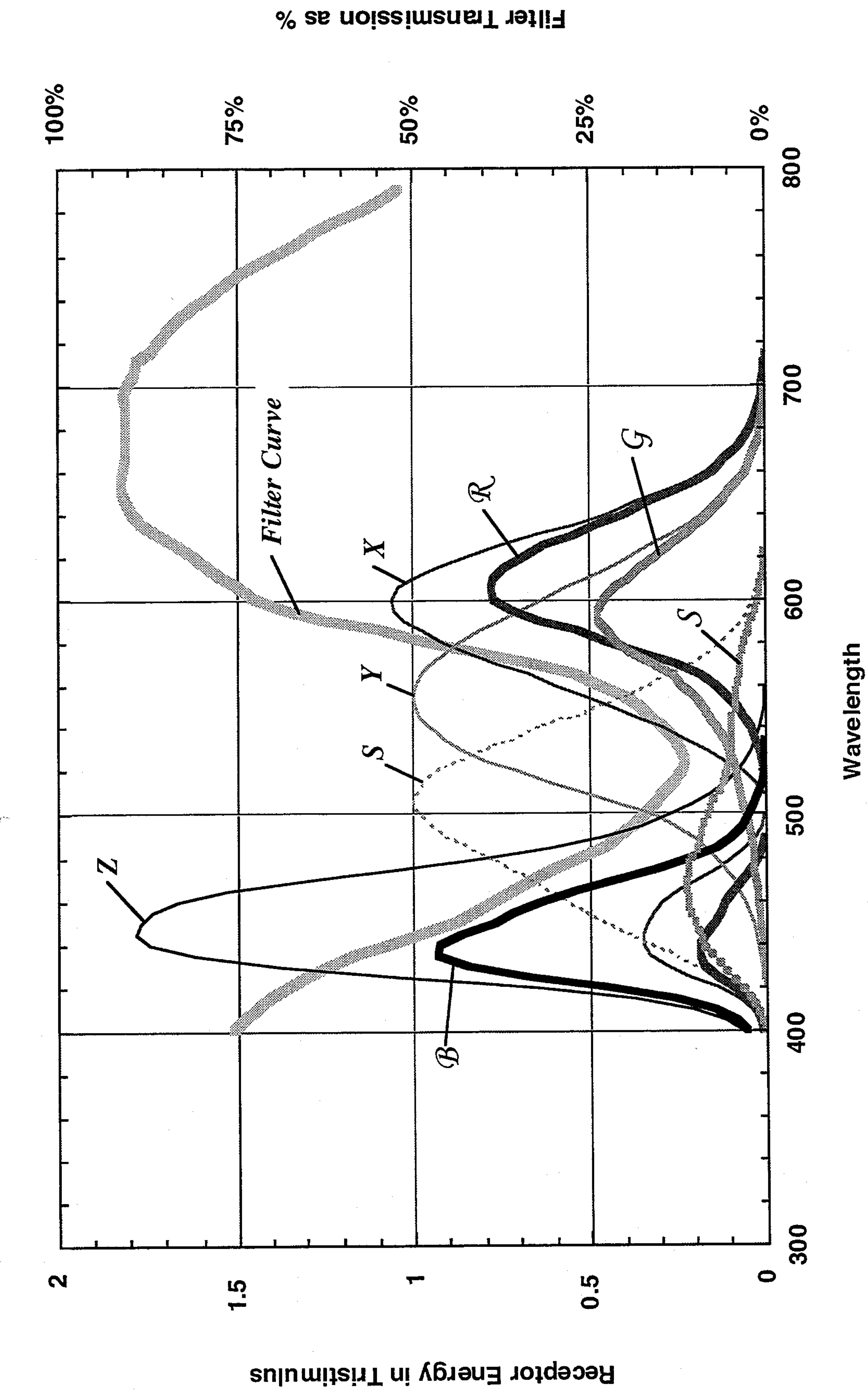
Filter 827 Eye Receptor Energy Transform Curves
Filter Transmission as %
100%
75%
50%
25%
0%
Receptor Energy in Tristimulus
2
1.5
1
0.5
0
300
400
500
600
700
800
Wavelength
Filter Curve
Z
X
Y
S
S
R
G
B


Filter 828 Eye Receptor Energy Transform Curves
Filter Transmission as %
100%
75%
50%
25%
0%
Receptor Energy in Tristimulus
2
1.5
1
0.5
0
300
400
500
600
700
800
Wavelength
Filter Curve
Z
X
Y
S
S
R
G
B

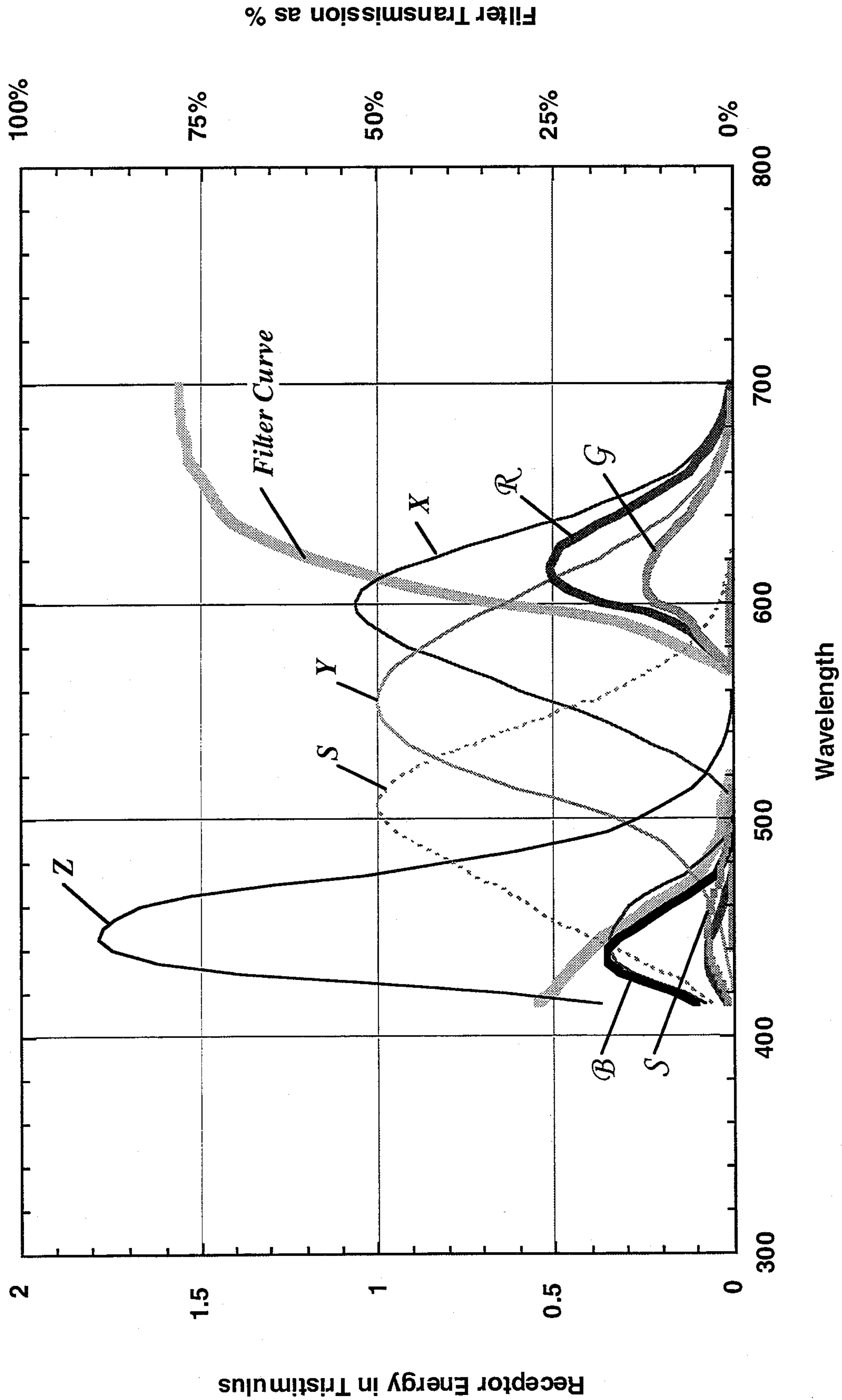
Filter 829 Eye Receptor Energy Transform Curves



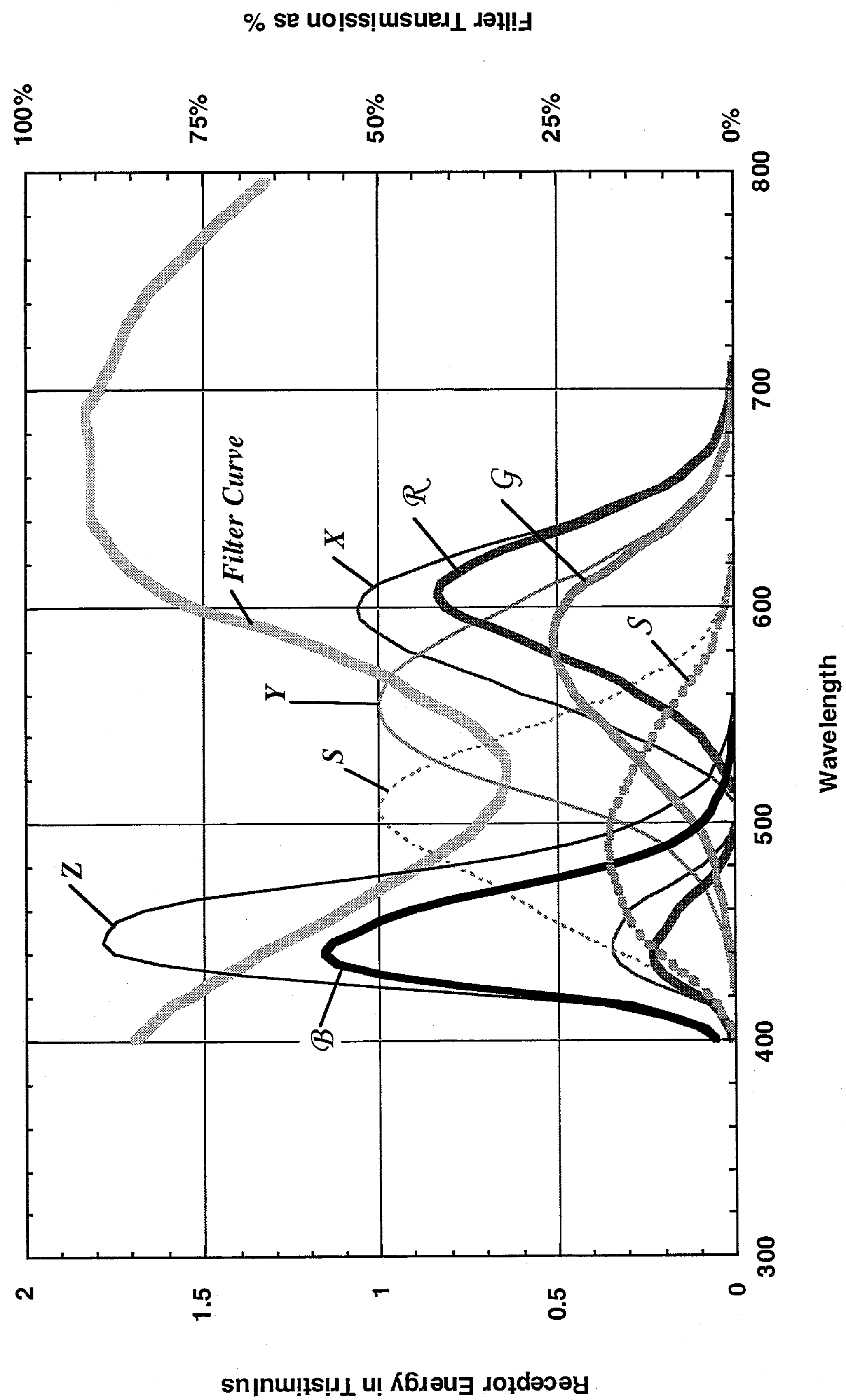
Filter 830 Eye Receptor Energy Transform Curves

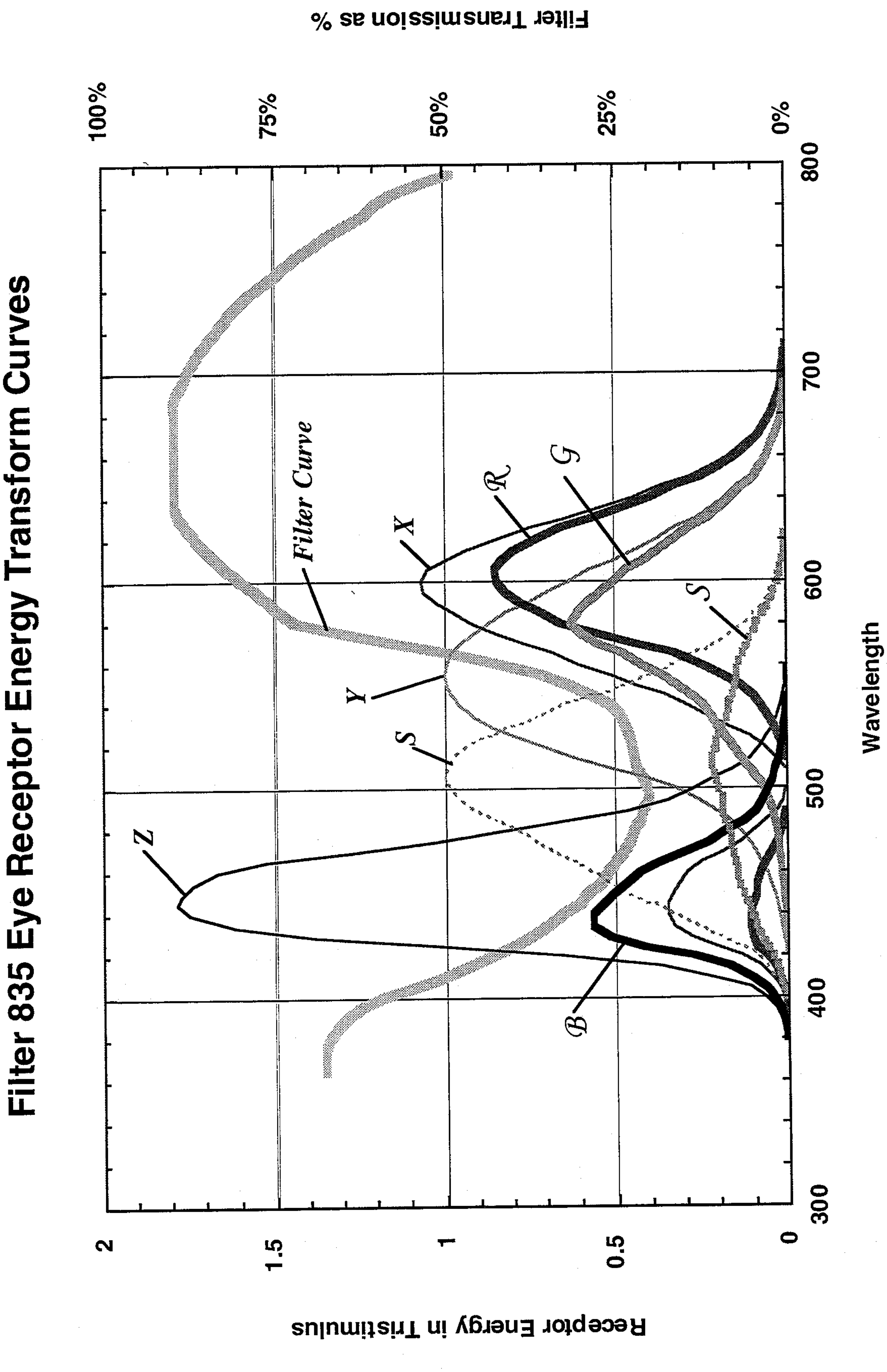


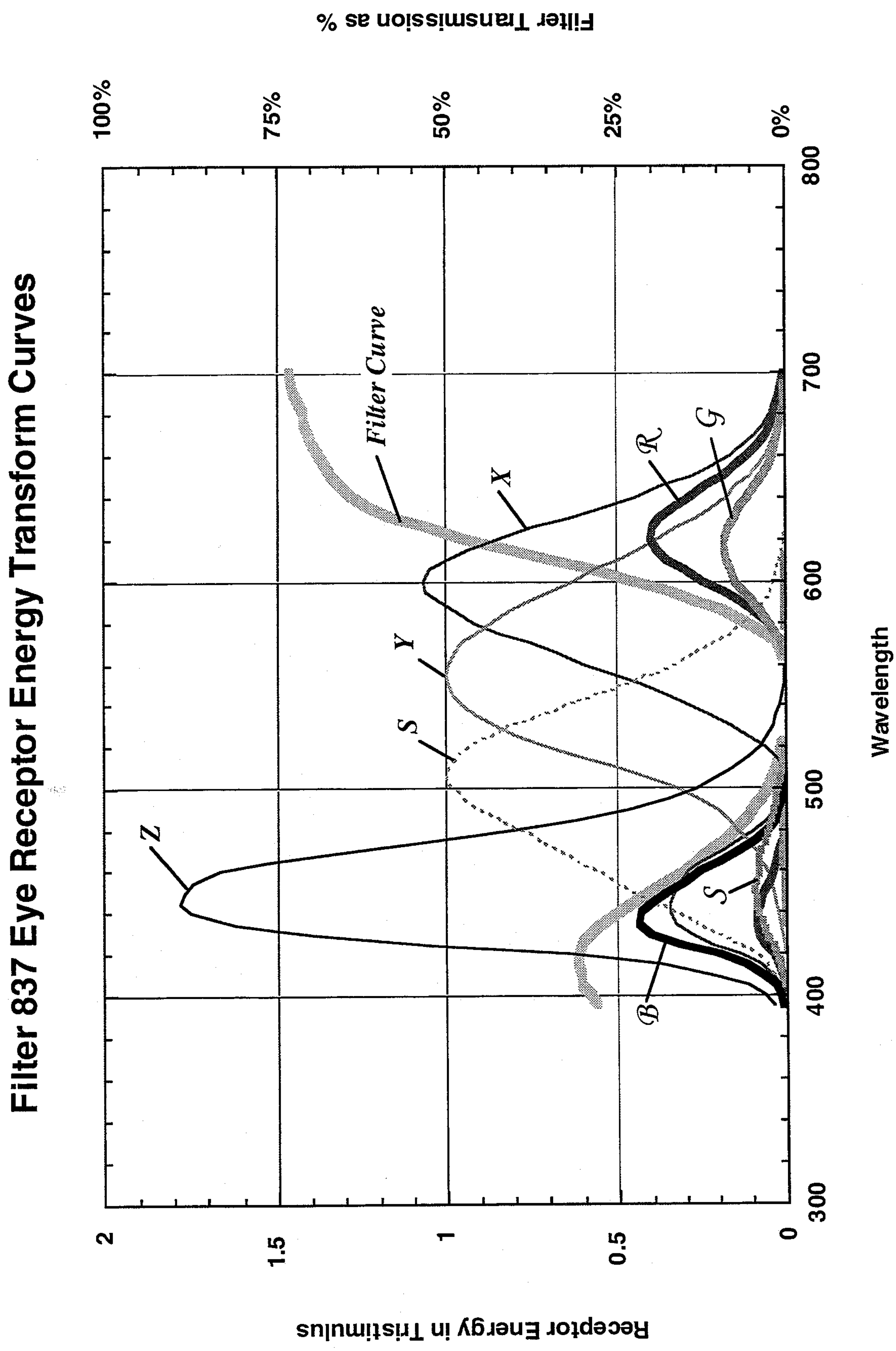
Filter 832 Eye Receptor Energy Transform Curves



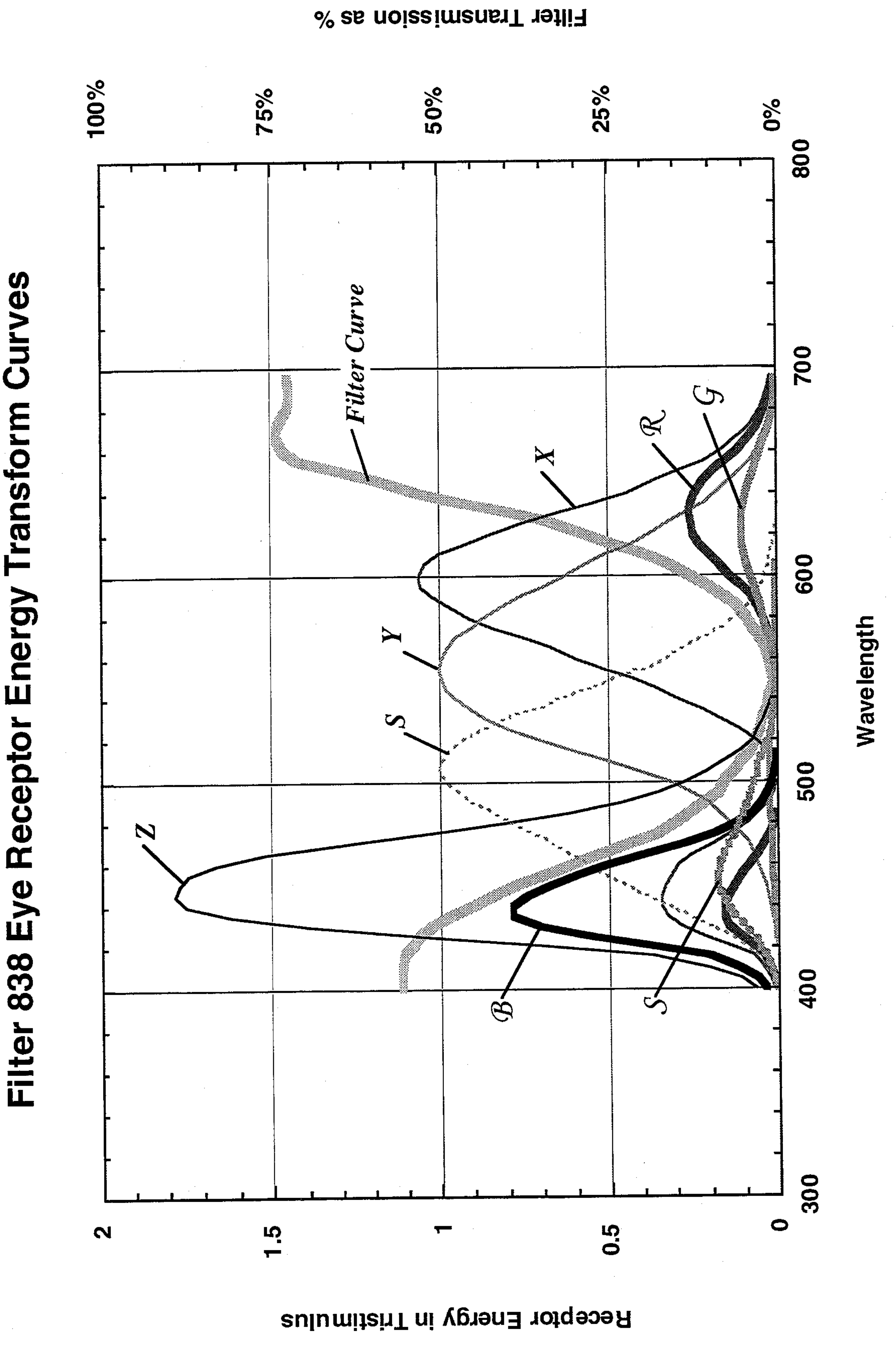
Filter 834 Eye Receptor Energy Transform Curves

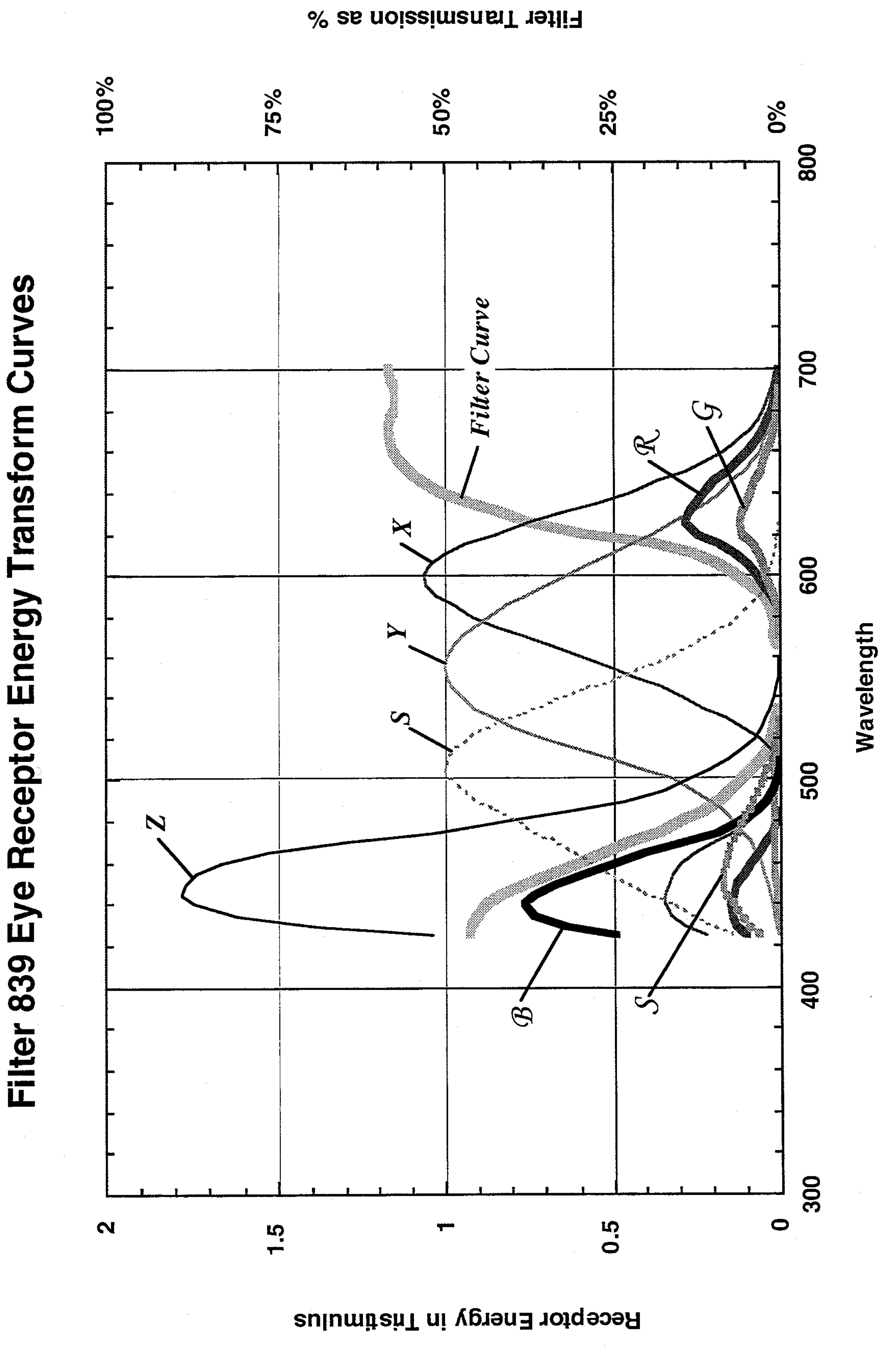


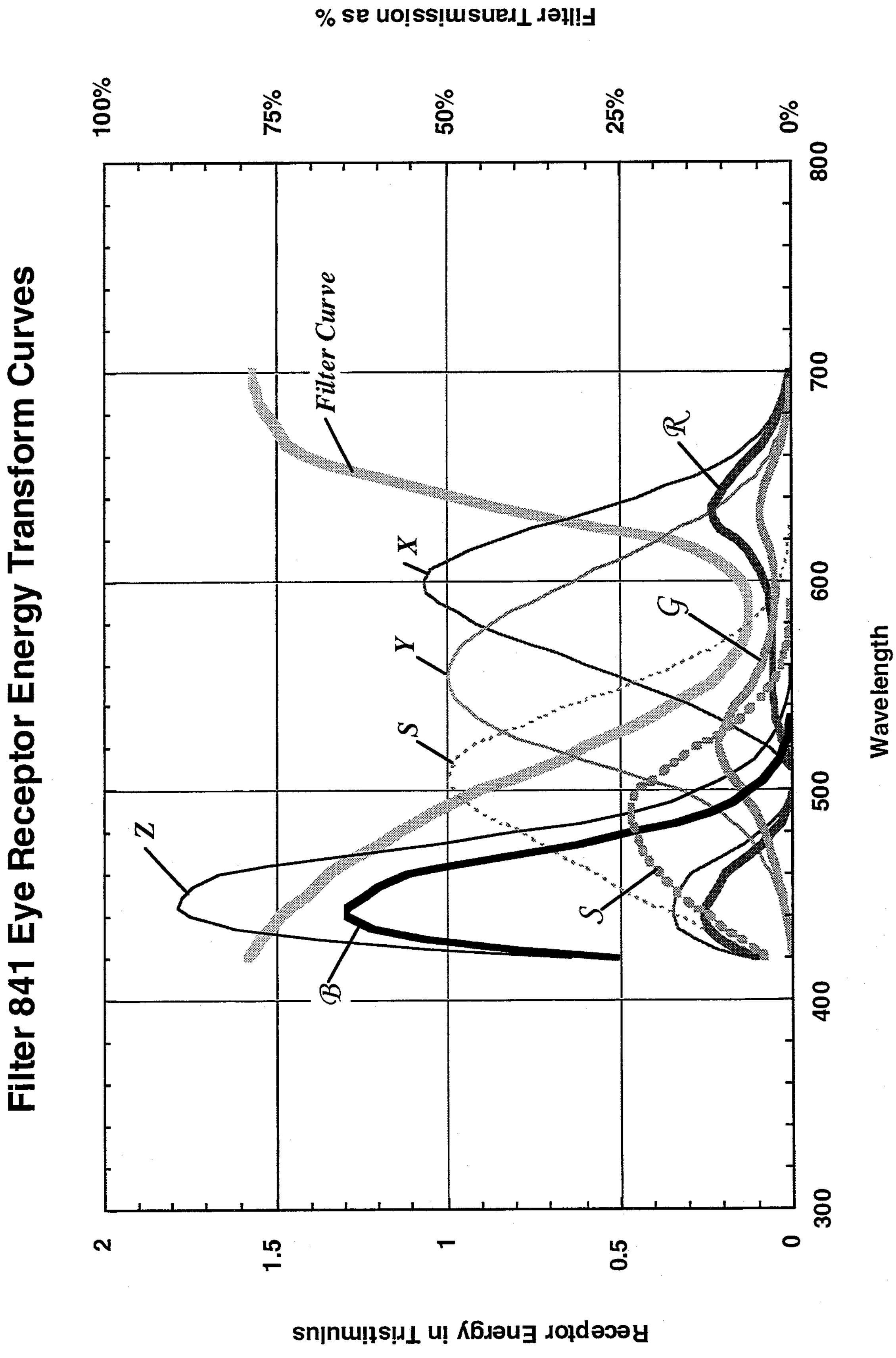

Filter 835 Eye Receptor Energy Transform Curves
Filter Transmission as %
100%
75%
50%
25%
0%
Receptor Energy in Tristimulus
2
1.5
1
0.5
0
300
400
500
600
700
800
Wavelength
Filter Curve
Z
Y
X
S
S
R
G
B

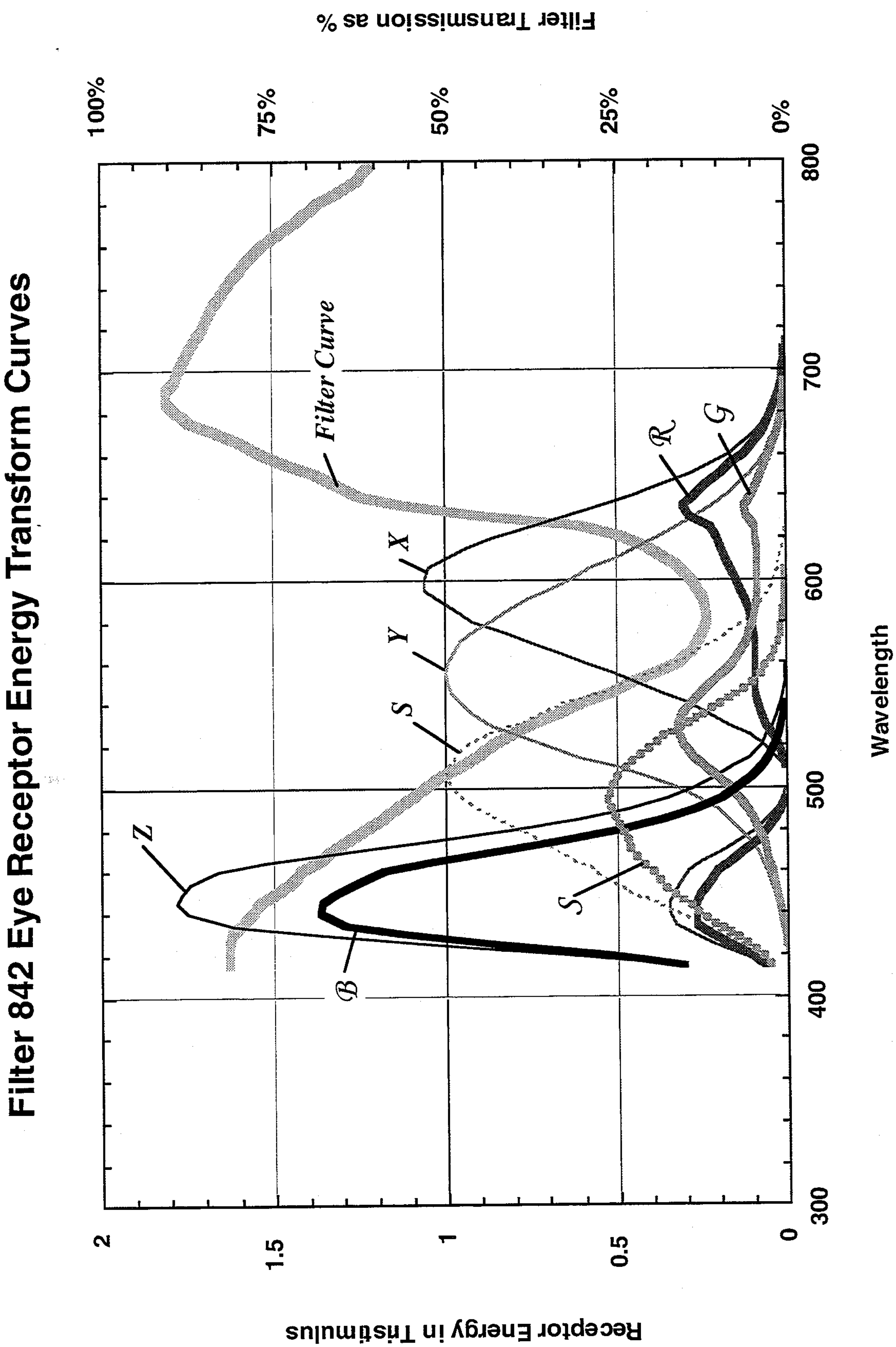


Filter 837 Eye Receptor Energy Transform Curves
Filter Transmission as %
100%
75%
50%
25%
0%
2
1.5
1
0.5
0
Receptor Energy in Tristimulus
300
400
500
600
700
800
Wavelength
Filter Curve
X
Y
Z
S
R
G
B

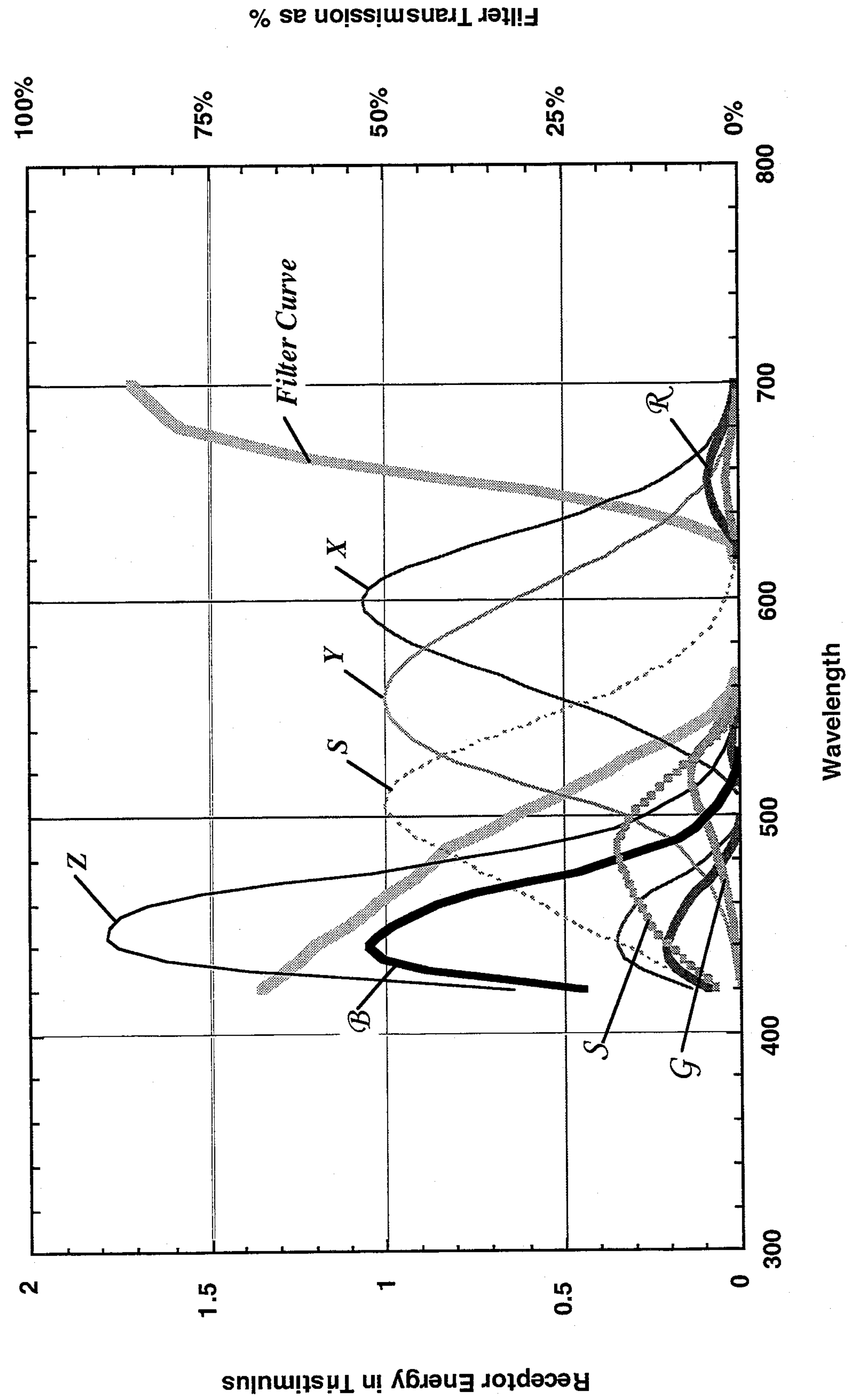

Filter 838 Eye Receptor Energy Transform Curves
Filter Transmission as %
100%
75%
50%
25%
0%
Receptor Energy in Tristimulus
2
1.5
1
0.5
0
Wavelength
300
400
500
600
700
800
Z
S
Y
X
Filter Curve
R
G
B
S


Filter 839 Eye Receptor Energy Transform Curves
Filter Transmission as %
100%
75%
50%
25%
0%
Receptor Energy in Tristimulus
2
1.5
1
0.5
0
Wavelength
300
400
500
600
700
800
Z
X
Y
S
Filter Curve
R
G
B
S

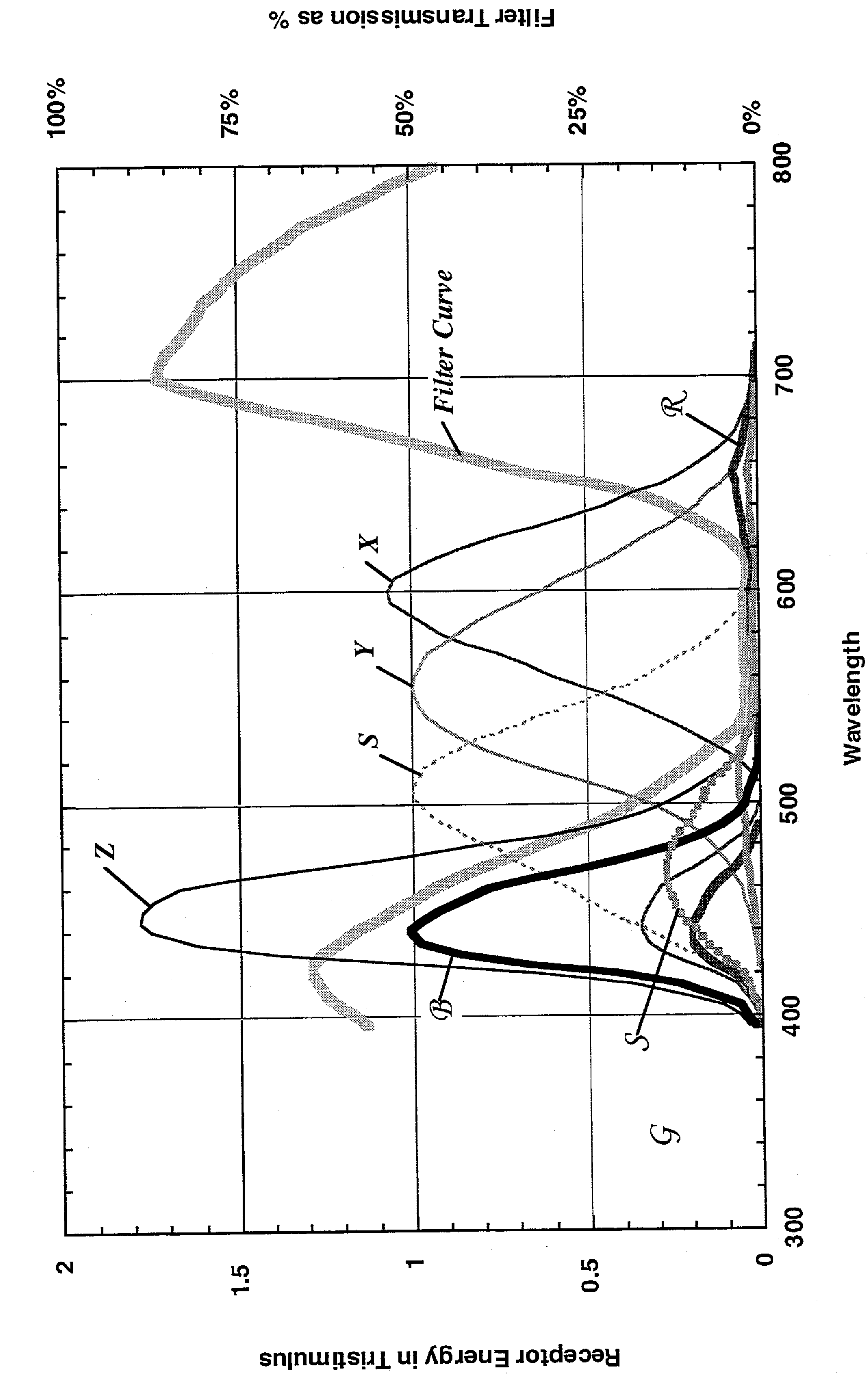

Filter 841 Eye Receptor Energy Transform Curves
Filter Transmission as %
100%
75%
50%
25%
0%
Receptor Energy in Tristimulus
2
1.5
1
0.5
0
Wavelength
300
400
500
600
700
800
Filter Curve
Z
X
Y
S
B
S
G
R

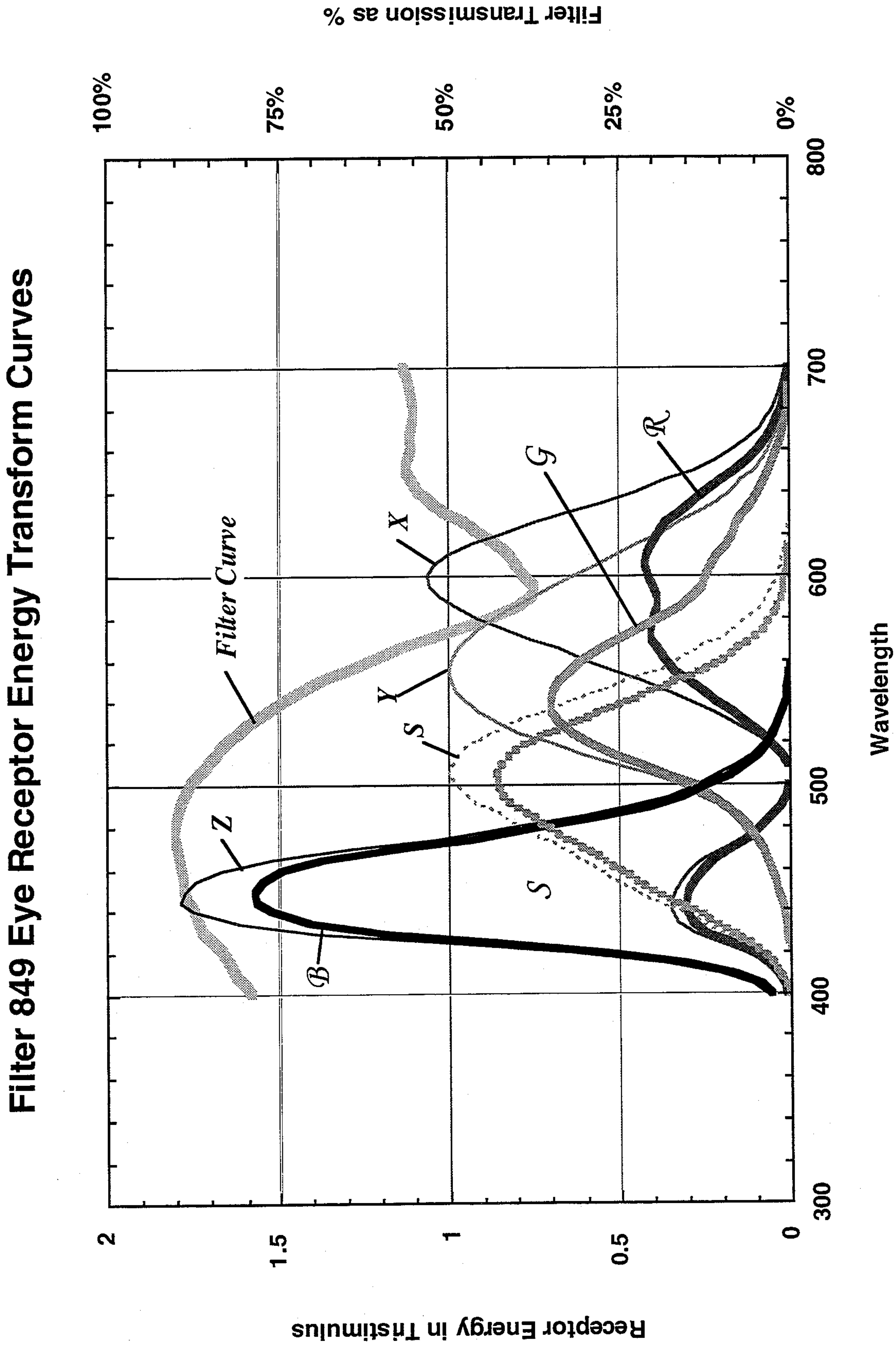

Filter 842 Eye Receptor Energy Transform Curves
Filter Transmission as %
100%
75%
50%
25%
0%
Receptor Energy in Tristimulus
2
1.5
1
0.5
0
Wavelength
300
400
500
600
700
800
Filter Curve
Z
X
Y
S
S
B
R
G

Filter 843 Eye Receptor Energy Transform Curves

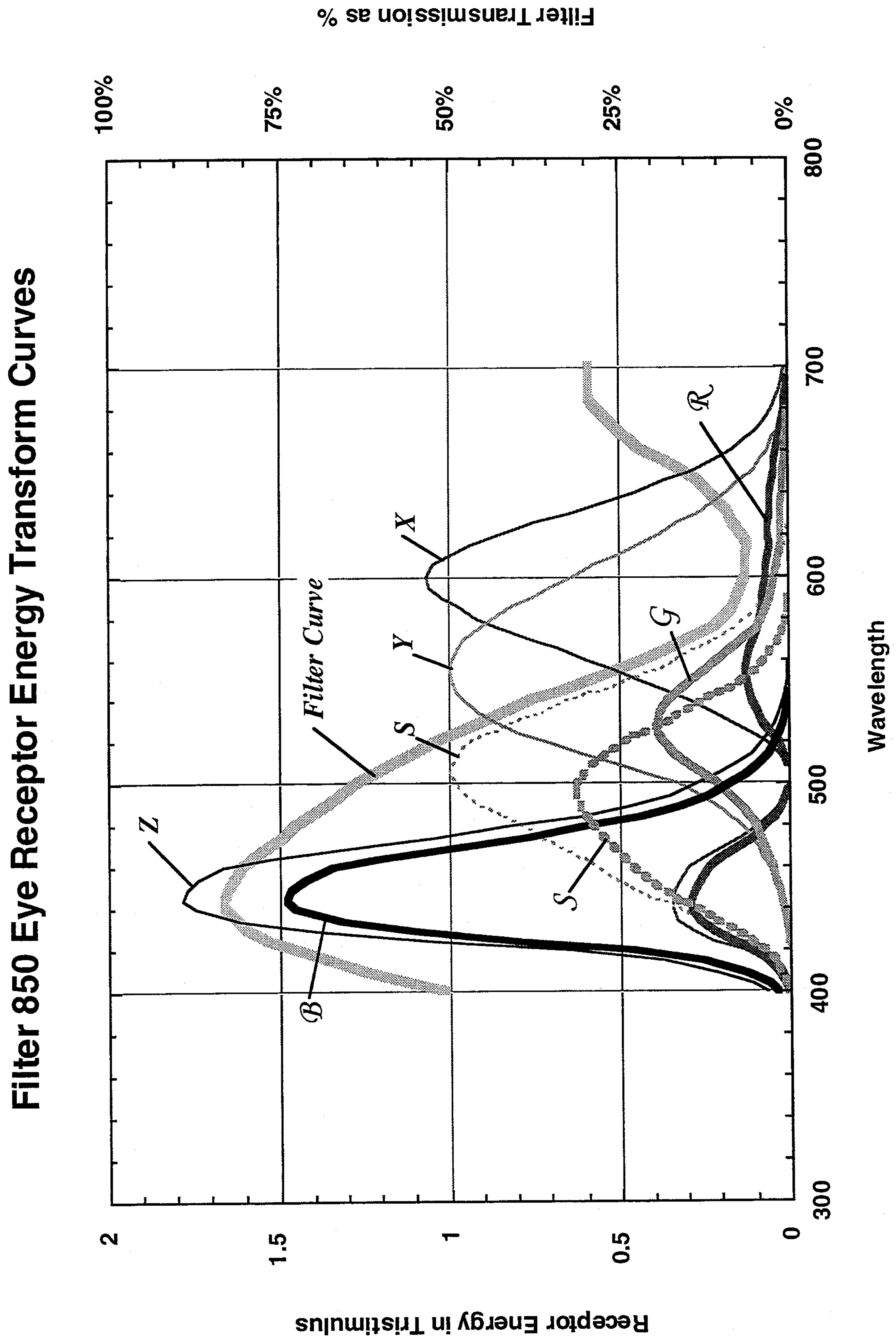


Filter 846 Eye Receptor Energy Transform Curves

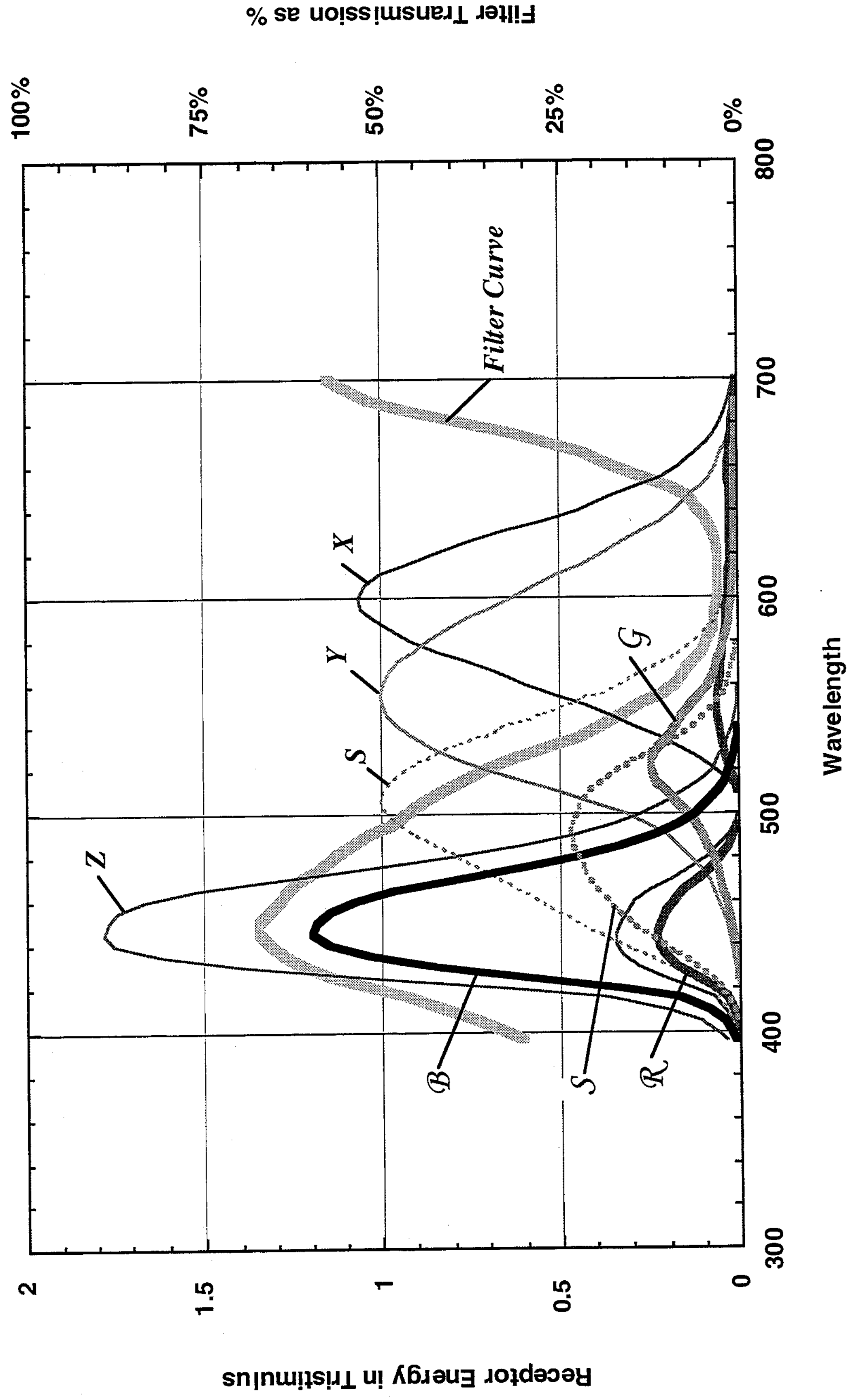


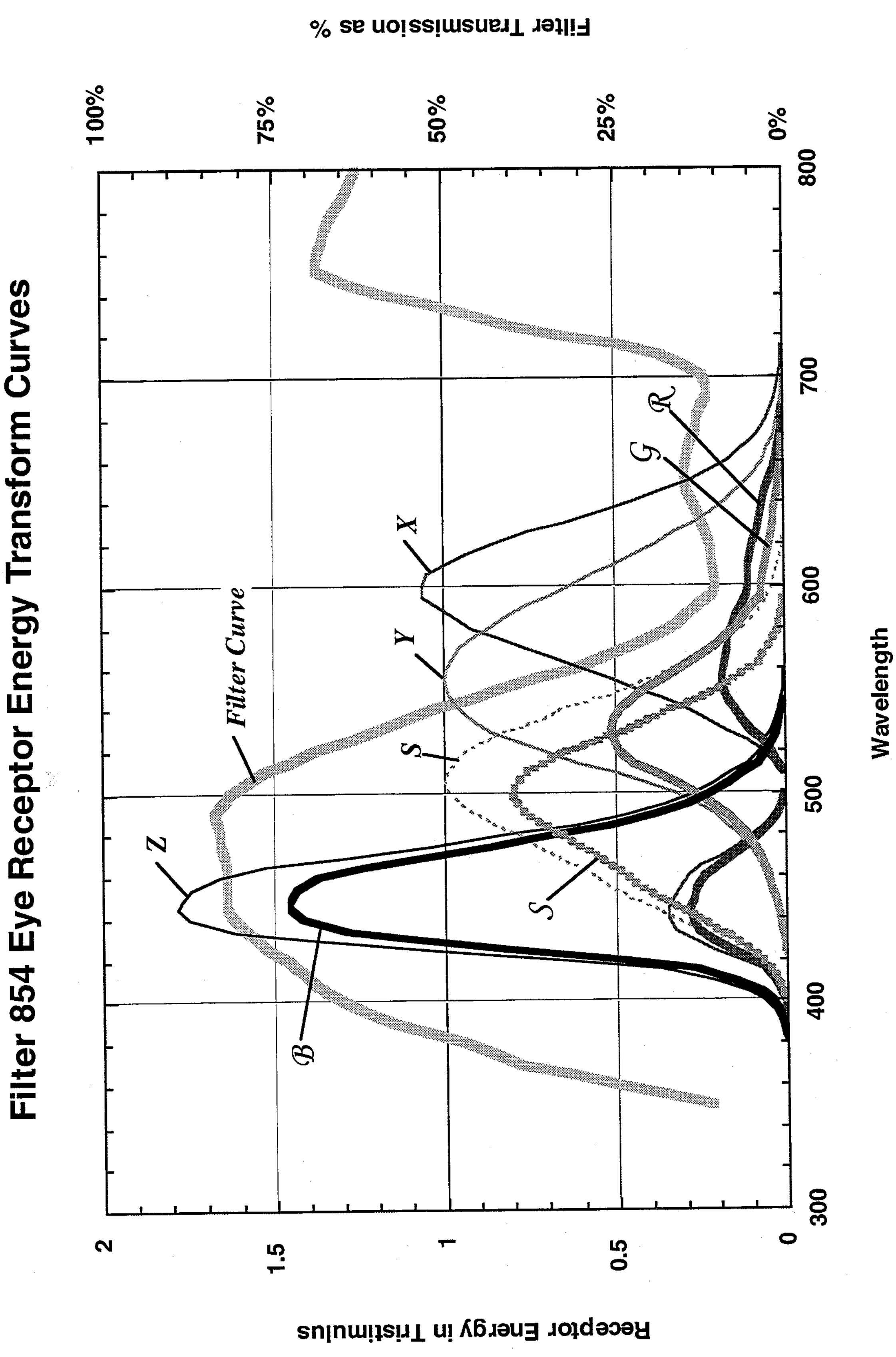


Filter 849 Eye Receptor Energy Transform Curves
Filter Transmission as %
100%
75%
50%
25%
0%
Receptor Energy in Tristimulus
2
1.5
1
0.5
0
Wavelength
300
400
500
600
700
800
Filter Curve
Z
B
X
Y
S
S
G
R

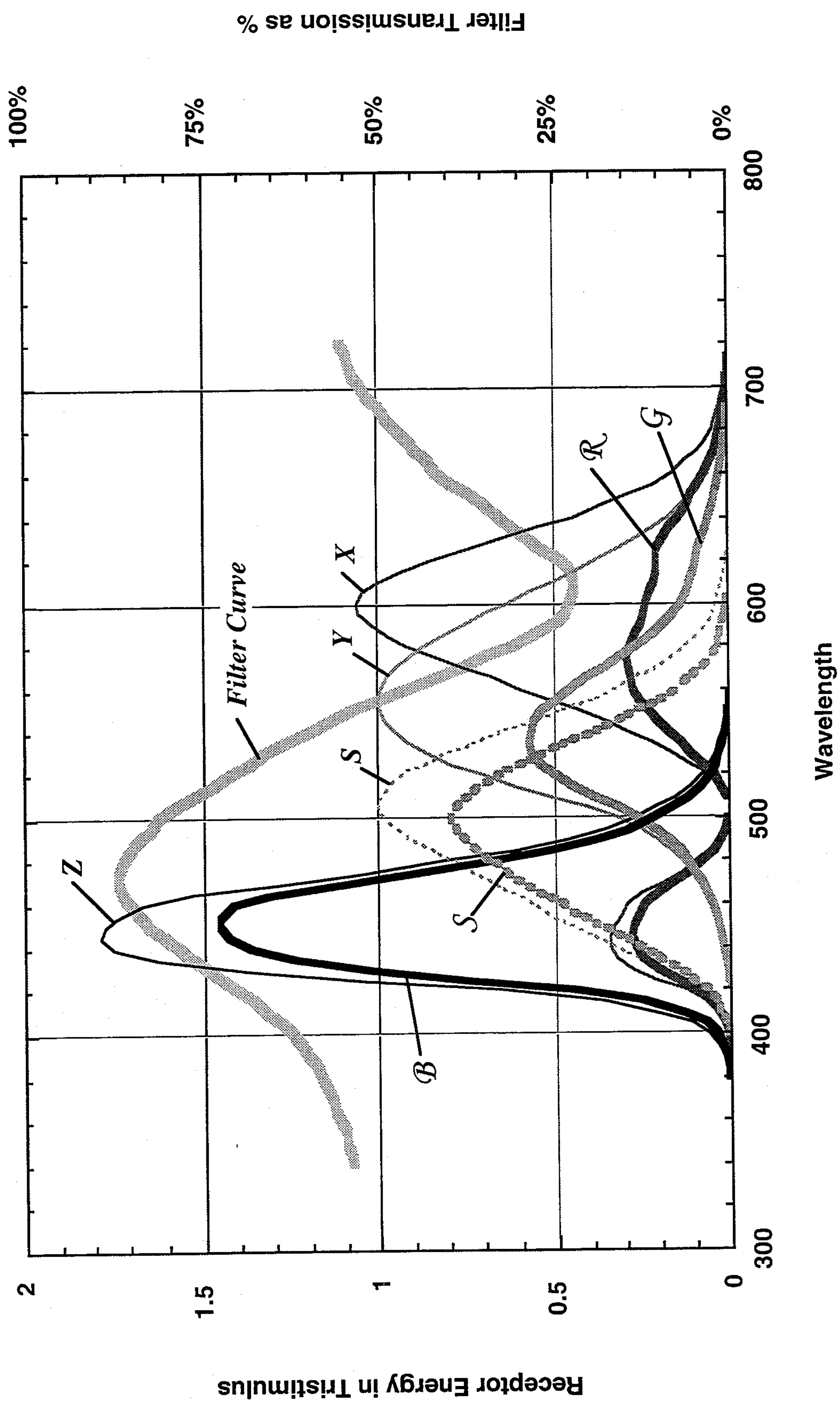

Filter 850 Eye Receptor Energy Transform Curves
Filter Transmission as %
100%
75%
50%
25%
0%
Receptor Energy in Tristimulus
2
1.5
1
0.5
0
300
400
500
600
700
800
Wavelength
Z
Filter Curve
S
Y
X
G
R
S
B

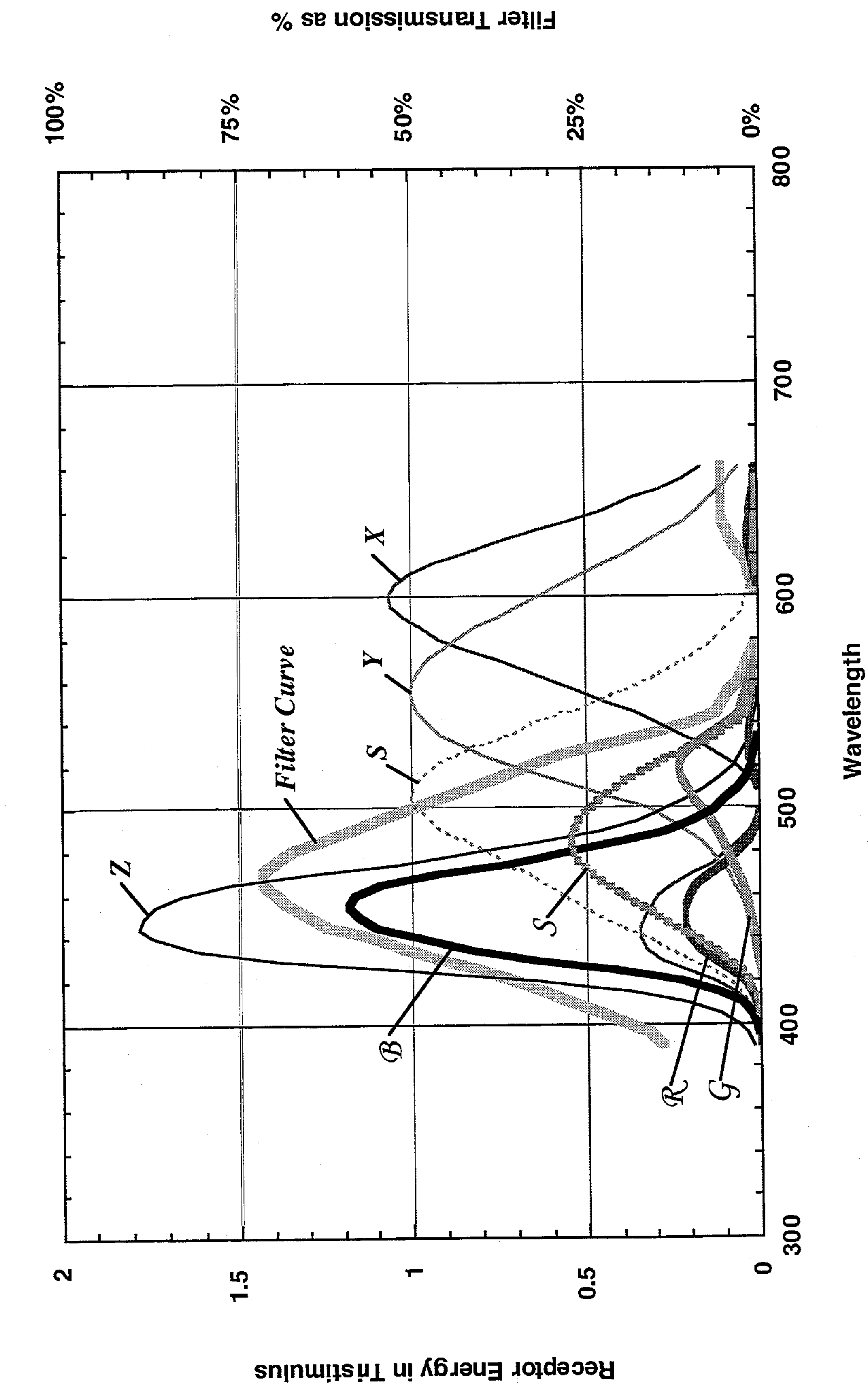
Filter 851 Eye Receptor Energy Transform Curves



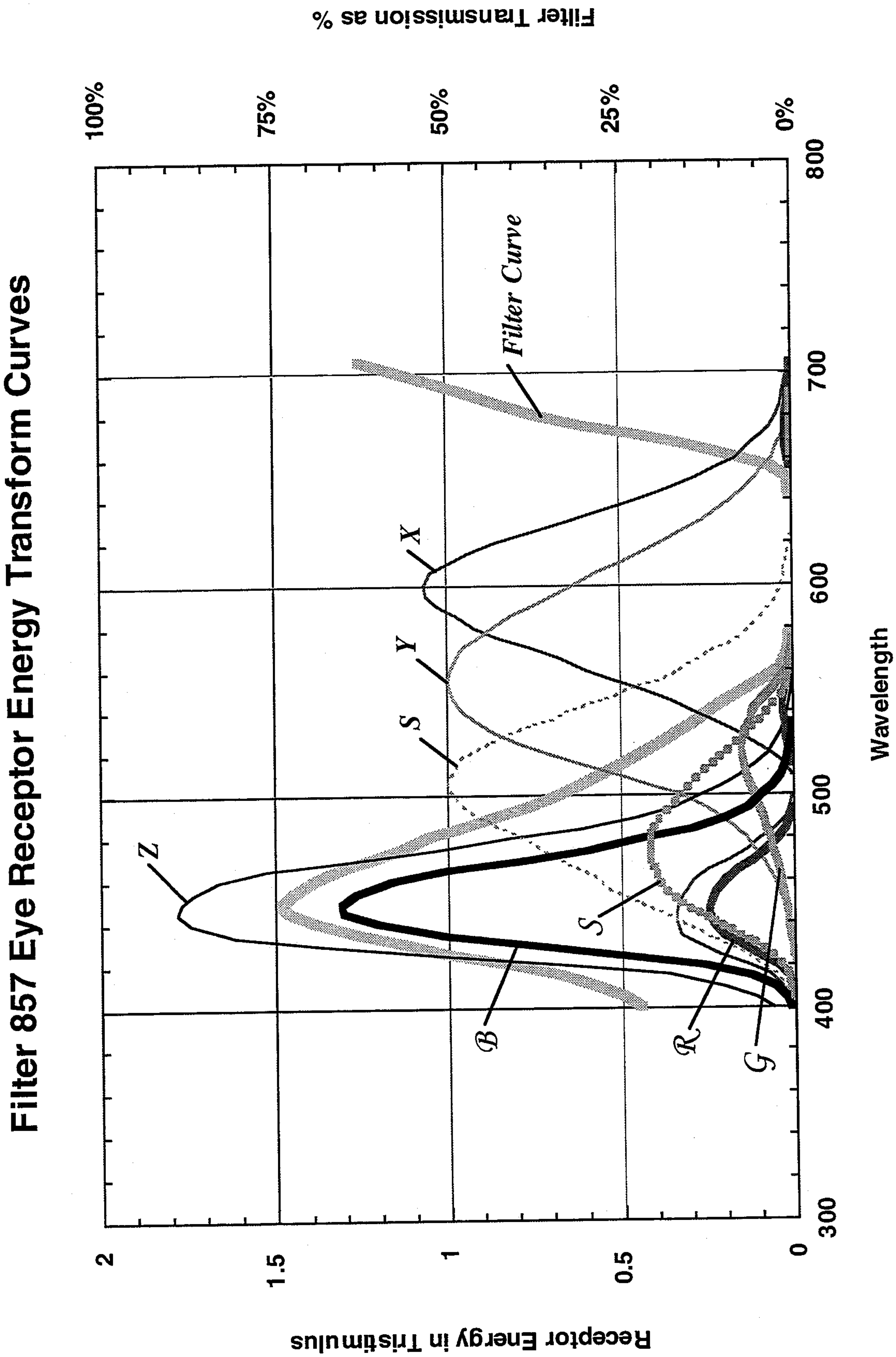

Filter 854 Eye Receptor Energy Transform Curves
Filter Transmission as %
100%
75%
50%
25%
0%
Receptor Energy in Tristimulus
2
1.5
1
0.5
0
Wavelength
300
400
500
600
700
800
Filter Curve
Z
X
Y
S
S
B
G
R

Filter 855 Eye Receptor Energy Transform Curves

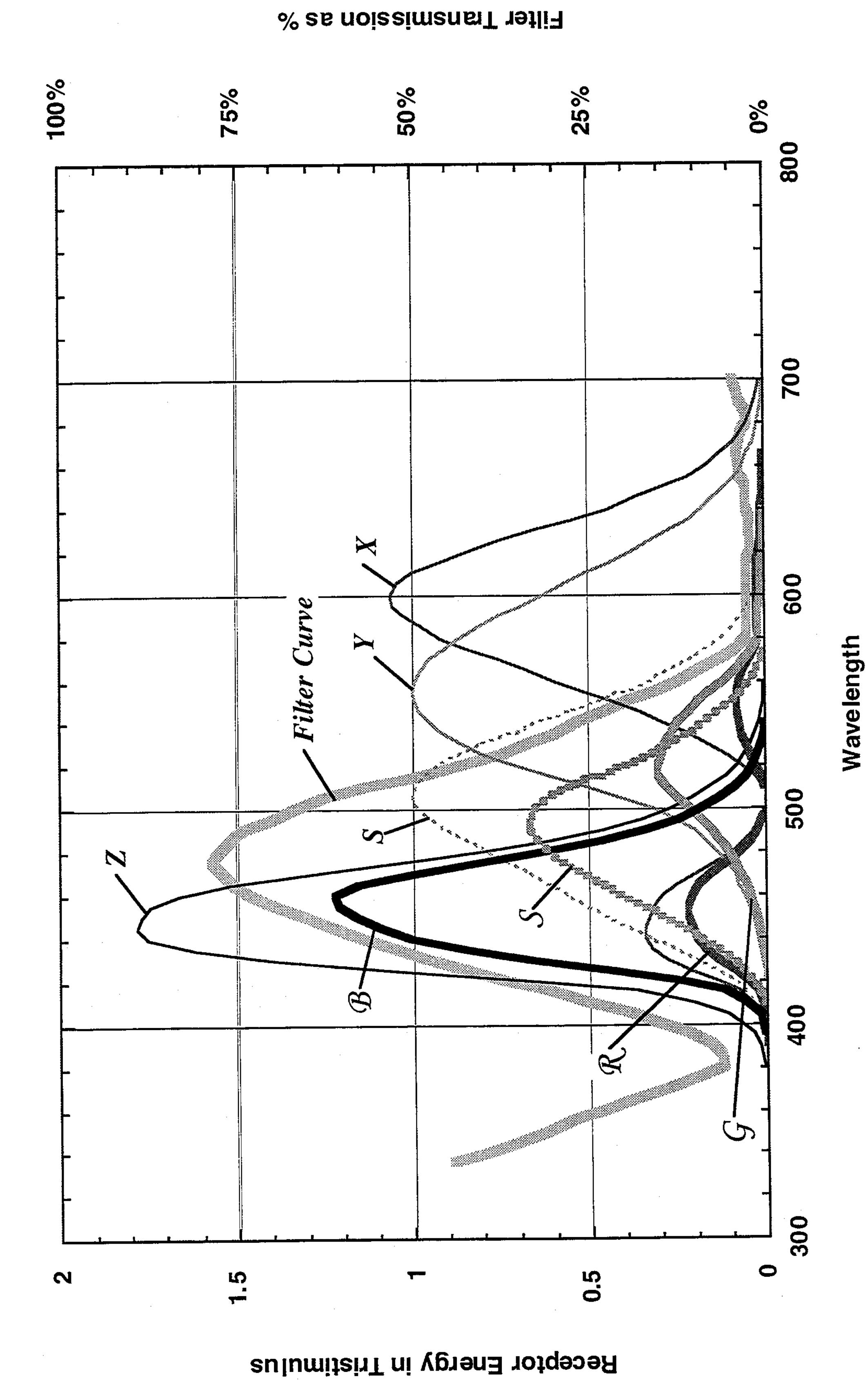


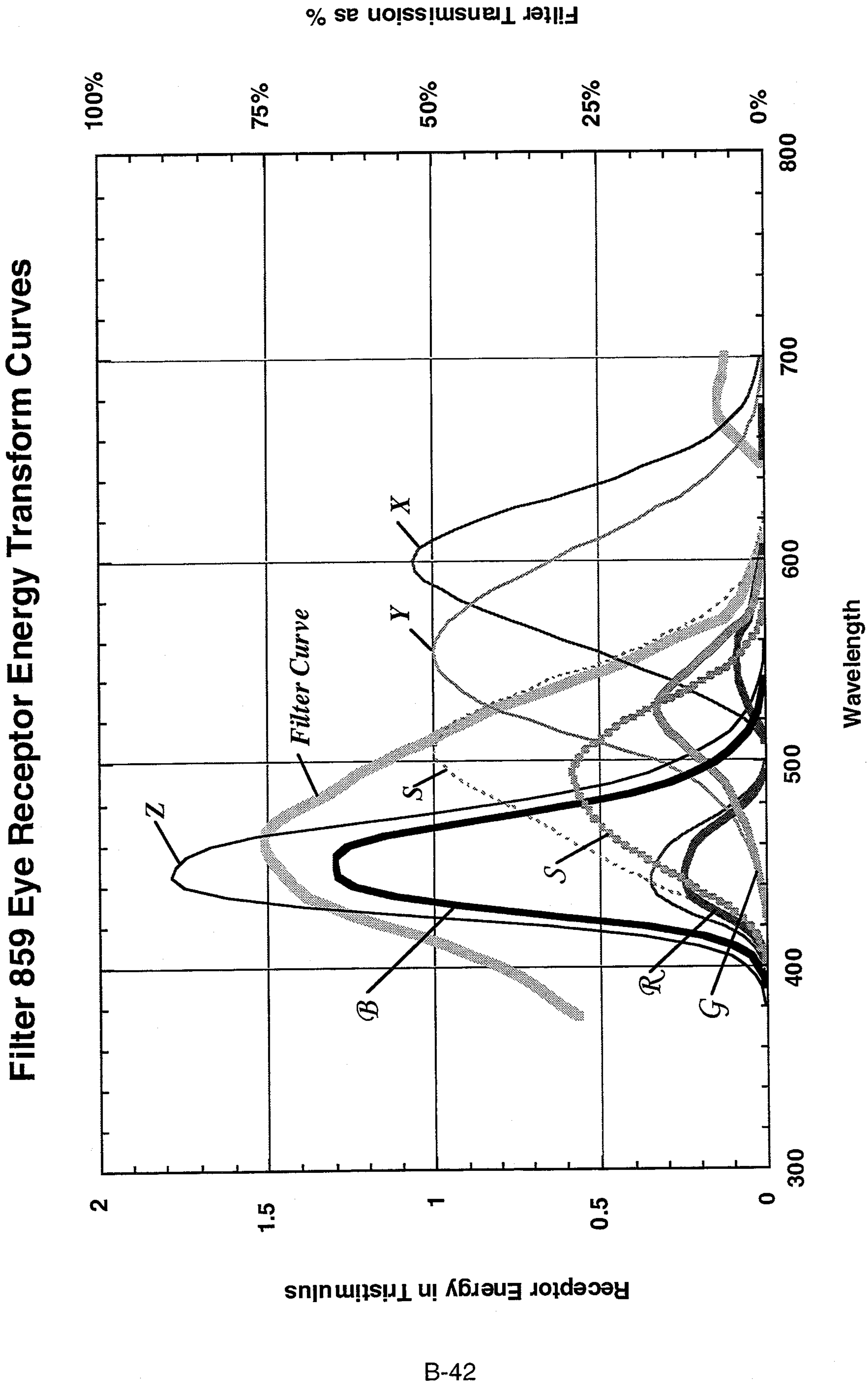


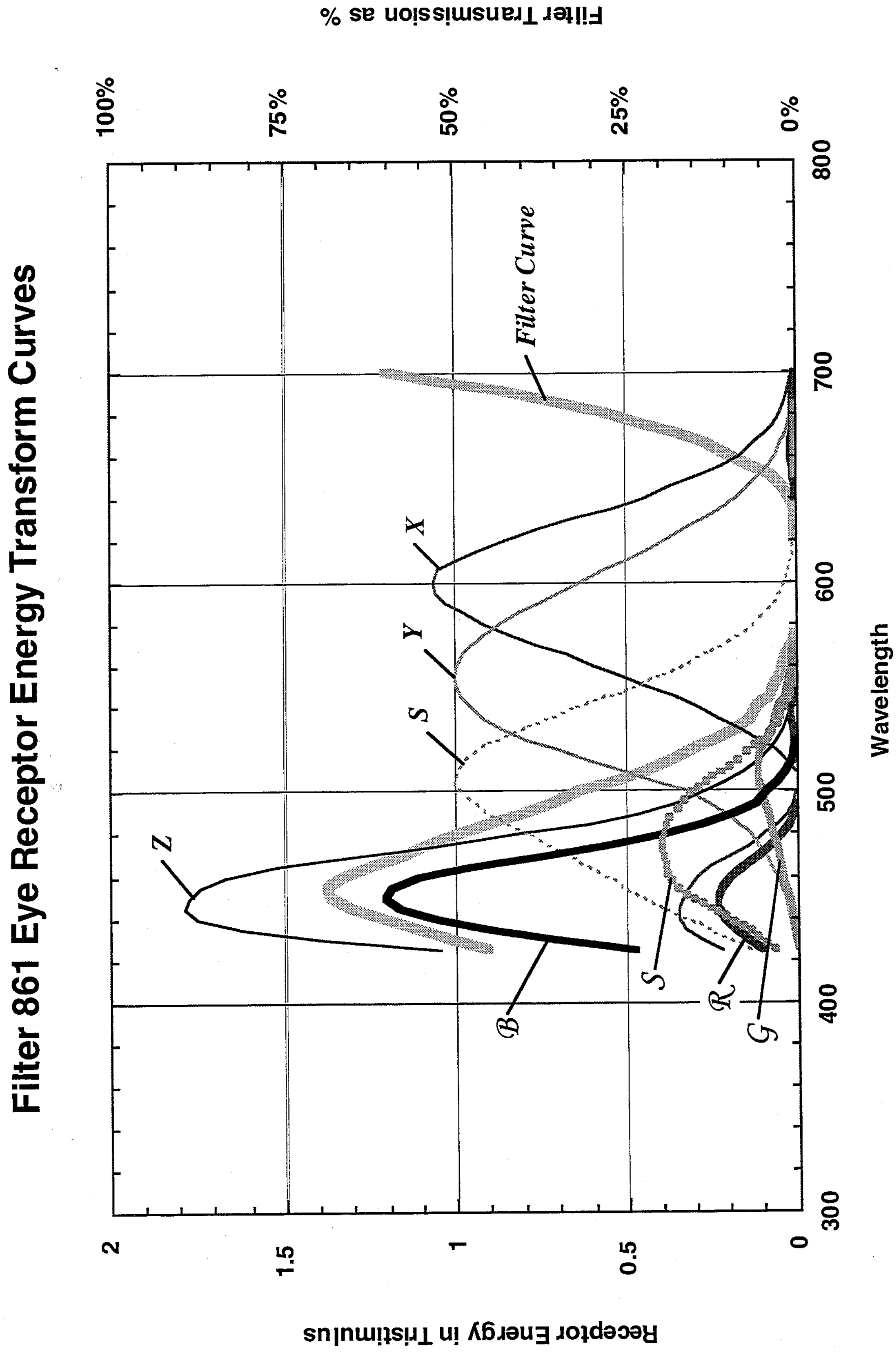
Filter 856 Eye Receptor Energy Transform Curves

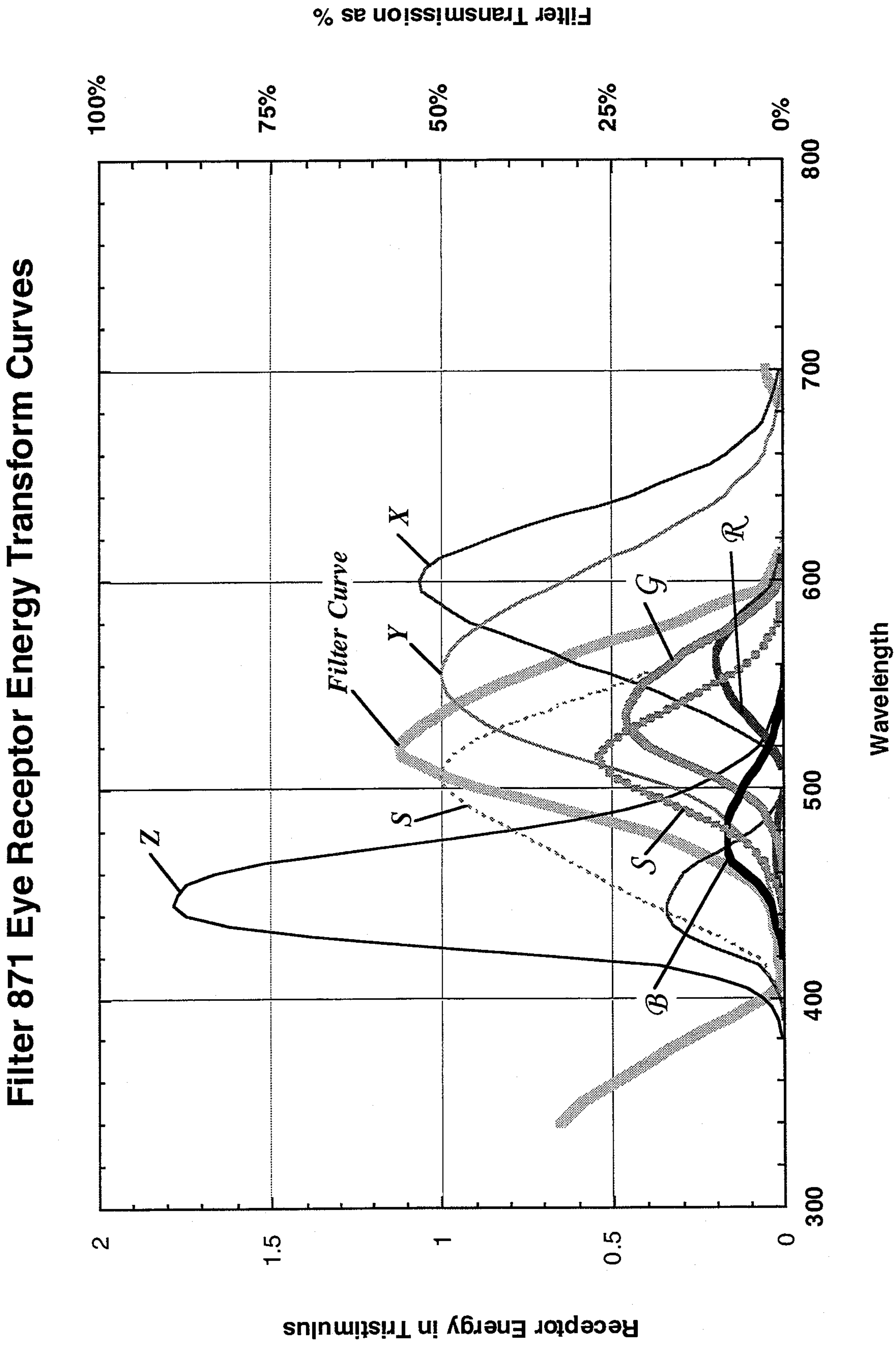

Filter 857 Eye Receptor Energy Transform Curves
Filter Transmission as %
100%
75%
50%
25%
0%
Receptor Energy in Tristimulus
2
1.5
1
0.5
0
Wavelength
300
400
500
600
700
800
Filter Curve
X
Y
S
Z
S
B
R
G

Filter 858 Eye Receptor Energy Transform Curves



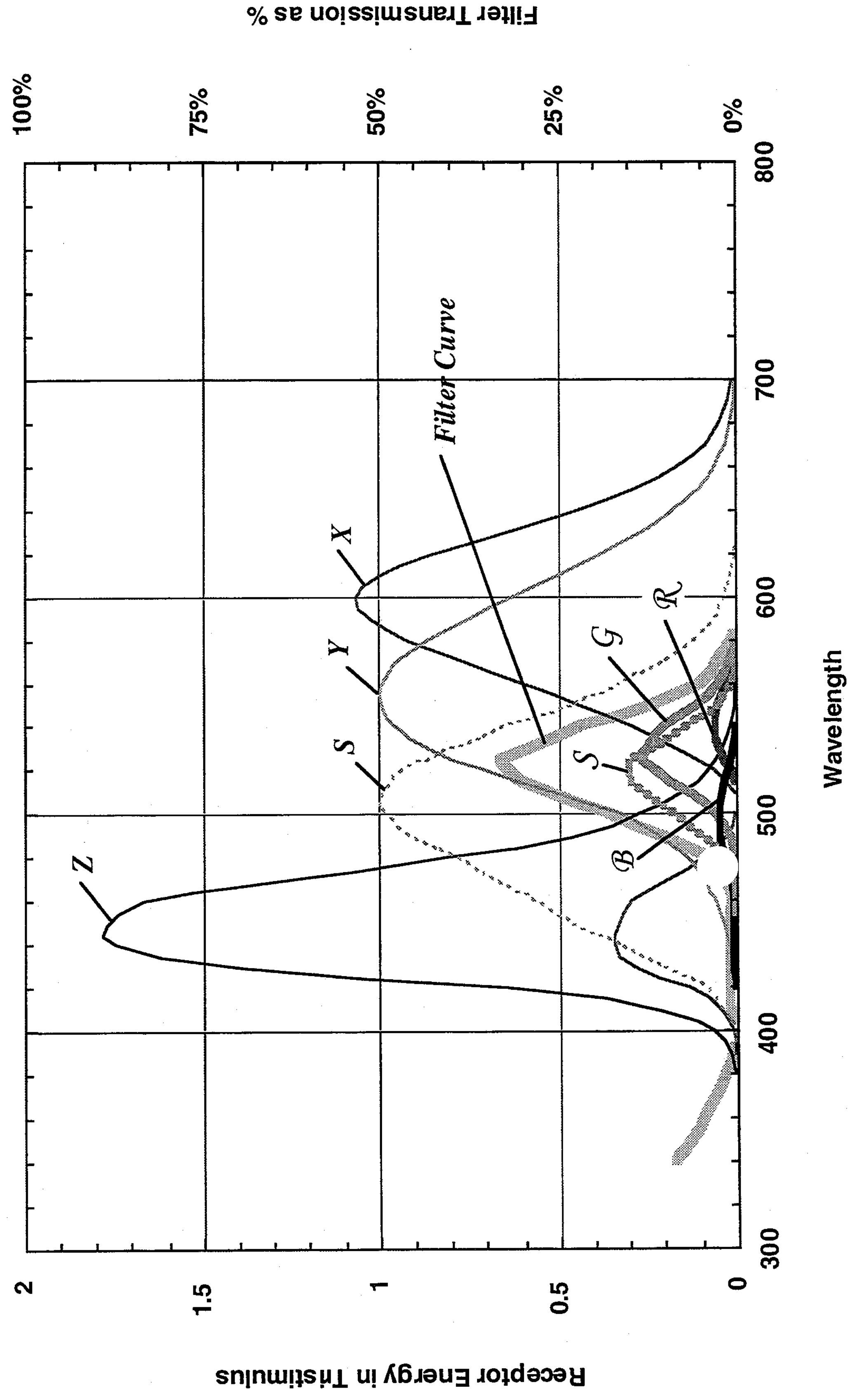

Filter 859 Eye Receptor Energy Transform Curves
Filter Transmission as %
100%
75%
50%
25%
0%
Receptor Energy in Tristimulus
2
1.5
1
0.5
0
300
400
500
600
700
800
Wavelength
Z
X
Y
Filter Curve
S
S
B
R
G


Filter 861 Eye Receptor Energy Transform Curves
Filter Transmission as %
100%
75%
50%
25%
0%
Receptor Energy in Tristimulus
2
1.5
1
0.5
0
Wavelength
300
400
500
600
700
800
Z
X
Y
S
Filter Curve
B
S
R
G

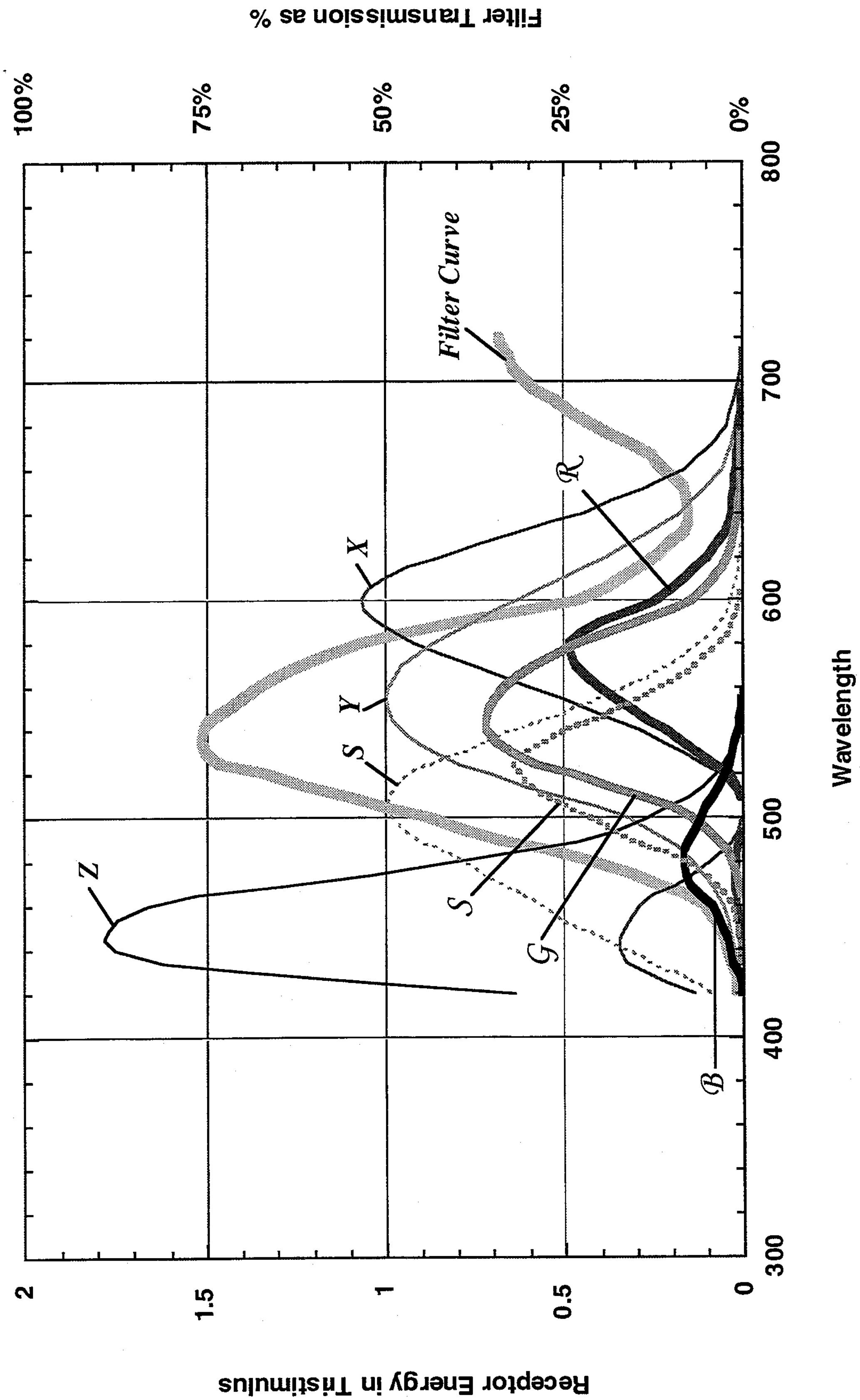


Filter 871 Eye Receptor Energy Transform Curves
Receptor Energy in Tristimulus
Filter Transmission as %
Wavelength
0
0.5
1
1.5
2
0%
25%
50%
75%
100%
300
400
500
600
700
800
Z
X
Y
S
S
G
R
B
Filter Curve

Filter 874 Eye Receptor Energy Transform Curves



Filter 878 Eye Receptor Energy Transform Curves



Appendix C
DISCUSSION OF HUE ANALYSIS

HUE ANALYSIS OF TEST RESULTS

BACKGROUND OF THEORY

In 1872 Ewald Hering proposed a theory of vision based on a six-factor response on the part of the human eye: white-black, yellow-blue, red-green.[63] This theory was based on empirical psychological response observations as opposed to having a physiological base at the time. This theory of vision, which became known as the Hering Opponent-Color Theory, while it appeared to be psychologically valid and useful in that regard, was heavily criticized for many years[64] because it seemed to be at variance with the three-cone physiological construction of the eye. Nevertheless, since it appeared to reflect the psychological response of individuals to color better than other theories (and was supported by a significant amount of psychological reaction data), it was retained in the scientific literature for that purpose.

The Hering Opponent-Color Theory was quantified in 1955 by Leo M. Hurvich and Dorothea Jameson, who derived equations for the psychological response of observers to its basic tenants.[65] These response equations, which used the C.I.E. 1931 Colorimetric Standard Observer as the base, are

$$
\begin{aligned}
B_\lambda &= 13.0682\bar{x}_\lambda + 0.2672\bar{z}_\lambda \\
G_\lambda &= 0.6736\bar{x}_\lambda + 14.0018\bar{y}_\lambda + 0.0040\bar{z}_\lambda \\
Y_\lambda &= -0.0039\bar{x}_\lambda + 13.4680\bar{y}_\lambda - 0.1327\bar{z}_\lambda \\
R_\lambda &= 0.3329\bar{x}_\lambda + 13.0012\bar{y}_\lambda - 0.0011\bar{z}_\lambda
\end{aligned}
$$

where $\bar{x}_\lambda$, $\bar{y}_\lambda$, $\bar{z}_\lambda$ are the C.I.E. tri-stimulus values for an equal energy spectrum.

(The nomenclature for these equations is independent of that used in the rest of this report.)

While these equations were derived before the time when the physiological basis for the Opponent-Color Theory of Vision was discovered and are known to have some difficulties matching the full range of real observers response below 400 nm, it was thought that it would be worth running the equations for the filter transformations and seeing if a correlation existed between the test subject's reading speed, vision angle, eye span, and focal length.

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[63] Le Grand, pp. 466-468.
[64] Le Grand, p. 467.
[65] Jameson and Hurvich (1955-1956). See also Wyszecki and Stiles, pp. 446-449.

DISCUSSION OF HUE ANALYSIS USING EXPERIMENTAL DATA

Since its deviation nearly half a century ago, the Hurvich-Jameson adaptation of the Hering Opponent-Color Theory has been one of the predominant theories on human color vision. As a result, in our attempt to analyze the vision phenomenon being investigated in this study, several attempts to correlate the data on the basis of the Hurvich-Jameson equations were made. A raw energy and a normalized energy approach was explored extensively, along with investigation of several sets of individual channel analyses and energy difference variation from normal.

These analytical approaches all proved useless in shedding light on the phenomenon under investigation. However, when the rationalization energy level approach was tried, the Hurvich-Jameson equations did yield an interesting finding—not on the phenomenon under investigation, but on the nature and workings of the Hurvich-Jameson model. Since the Hurvich-Jameson model is widely reported and covered in the literature on human color vision, it was felt that it was worth reporting these findings even though they are not specifically germane to the understanding of the phenomenon under investigation. (Though they do say something about why the phenomenon has not been found and studied more widely and why the Hurvich-Jameson method does not work for analyzing it.)

If one uses the rationalized energy values to calculate the Hurvich-Jameson hue values, one comes up with the value set shown in Table C-1. These hue values can then be plugged into the test performance measurement table and hue receptor field energy values calculated as shown in Table C-2. If one then plots these hue receptor field energy values against the measured performance factors such as reading speed (used as the example here), one gets the receptor field energy plots shown in Figures C-1, C-2, C-3 and C-4.

If one looks at these plots, the first reaction is that the computerized plotting system is muddled and the graphs mislabeled. This is actually not the case; the graphs are correct. Therein lies an interesting insight into how and why the Hurvich-Jameson equations work.

TABLE C-1. Hue Value Calculation Sheet.

Filter no.	Rationalized energy values			Calculated Hurvich-Jameson Hue values			
	$\mathcal{R}$	$\mathcal{G}$	$\mathcal{B}$	B	G	Y	R
NONE	33.33	33.33	33.33	444.510	444.403	444.376	444.430
802	43.40	32.66	23.94	573.588	428.137	436.498	439.021
804	34.78	35.31	29.91	462.548	471.044	471.403	470.573
805	38.52	39.16	22.32	509.328	522.439	524.280	521.912
806	46.29	48.03	5.68	606.421	641.327	645.912	639.830
807	48.45	48.36	3.19	633.986	644.549	650.742	644.904
809	51.50	46.94	1.56	673.417	622.628	631.845	627.481
810	45.21	44.77	10.02	593.461	596.499	601.505	597.149
811	46.42	38.52	15.06	610.642	508.093	516.561	516.198
813	54.54	41.89	3.57	713.671	549.815	563.491	562.775
815	58.36	41.35	0.28	762.784	539.725	556.698	557.088
817	59.93	38.81	1.26	783.486	503.045	522.290	524.523
818	61.93	34.13	3.95	810.343	436.134	458.851	464.298
819	61.72	33.44	4.83	807.914	426.725	449.549	455.361
825	36.37	30.56	33.07	484.158	403.497	407.024	409.361
826	41.34	29.22	29.44	548.138	381.351	389.418	393.578
828	41.97	29.71	28.32	556.010	387.876	396.250	400.241
830	41.88	26.83	31.29	555.646	347.632	357.078	362.775
832	52.28	23.64	24.08	689.638	295.929	315.029	324.769
834	38.06	29.25	32.69	506.052	384.052	389.455	392.921
837	45.88	20.19	33.93	608.632	251.986	267.294	277.785
841	23.73	18.25	58.02	325.578	239.751	237.968	245.078
842	25.32	21.79	52.89	344.976	288.311	286.402	291.715
849	27.11	30.33	42.56	365.622	406.605	402.750	403.322
850	18.55	21.74	59.71	258.369	292.185	284.839	288.795
851	17.15	18.05	64.81	241.393	241.394	234.385	240.265
855	24.06	28.52	47.42	327.105	383.246	377.655	378.689
856	14.34	15.66	70.01	206.064	209.851	201.525	208.258
857	14.87	12.52	72.61	213.743	165.598	158.948	167.666
858	15.25	21.15	63.60	216.320	286.139	276.370	280.002
871	22.49	58.11	19.40	299.133	798.579	779.972	762.974
878	33.35	56.30	10.35	438.540	765.905	756.768	743.080

TABLE C-2. Rationalized Hurvich-Jameson Hue Test Data Table.

	SUBJECTIVE FACTORS					QUANTITATIVE FACTOR				CALCULATED FACTORS							
Filter No.	Brightness	Clarity of Letters	Flicker Rating	Sustainability of Focus Rating	Perception Rating	Focal Length	Eye Span in Letters	Eye Span in Distance	Angle of Eye Span	Angle of Eye Span Increases as % of Normal	Reading Speed	Reading Speed as % of Normal	Focal Length Change From Normal (in inches)	Focal Length Change From Normal (in %)	Variance of Focal Length (in %)	Eye Span Tape Distance Variation	Eye Span Tape Distance Variation as %
NONE	0	0	0	0	0	14.125	3	0.300	1.22	100.00%	2:32	100.00%	0	100.00%	0.00%	0.000	0.00%
802	+1	+2	+2	+2	+1	14.7	6	0.625	2.44	200.20%	1:53	134.51%	0.575	104.07%	-4.07%	0.325	108.33%
804	+2	+2	+1	+1	+2	14.1	8	0.725	2.95	242.12%	1:45	144.76%	-0.025	99.82%	0.18%	0.425	141.67%
805	+3	+3	+2	+2	+2	15.2	8	0.750	2.83	232.34%	2:10	116.92%	1.075	107.61%	-7.61%	0.450	150.00%
806	+2	-1	0	+1	-1	14.2	3	0.325	1.31	107.76%	2:46	91.57%	0.075	100.53%	-0.53%	0.025	8.33%
807	-1	+1	+2	0	0	12.7	2.5	0.250	1.13	92.68%	2:42	93.83%	-1.425	89.91%	10.09%	-0.050	-16.67%
809	+1	+1	+1	+1	0	14	3.5	0.300	1.23	100.89%	2:58	85.39%	-0.125	99.12%	0.88%	0.000	0.00%
810	+1	0	+1	+1	0	13.4	2.5	0.250	1.07	87.84%	2:42	93.83%	-0.725	94.87%	5.13%	-0.050	-16.67%
811	+1	+2	+1	+2	+2	14.6	4.5	0.450	1.77	145.12%	2:19	109.35%	0.475	103.36%	-3.36%	0.150	50.00%
813	0	+1	+1	0	0	15	5	0.500	1.91	156.95%	2:47	91.02%	0.875	106.19%	-6.19%	0.200	66.67%
815	+2	+2	+1	+1	+2	14.2	3.5	0.250	1.01	82.89%	2:28	102.70%	0.075	100.53%	-0.53%	-0.050	-16.67%
817	+1	-1	+1	-1	0	13.75	3	0.250	1.04	85.61%	2:28	102.70%	-0.375	97.35%	2.65%	-0.050	-16.67%
818	0	+1	+1	-2	-1	13.2	2.5	0.200	0.87	71.34%	2:40	95.00%	-0.925	93.45%	6.55%	-0.100	-33.33%
819	-1	+1	+1	-2	-2	14.1	2	0.175	0.71	58.44%	2:45	92.12%	-0.025	99.82%	0.18%	-0.125	-41.67%
825	-1	0	+1	-2	+1	17.2	2.5	0.175	0.58	47.90%	2:51	88.89%	3.075	121.77%	-21.77%	-0.125	-41.67%
826	+1	+1	+2	0	0	15.2	3.25	0.275	1.04	85.18%	2:40	95.00%	1.075	107.61%	-7.61%	-0.025	-8.33%
828	+1	-1	+1	-2	0	15.2	2.5	0.175	0.66	54.21%	2:45	92.12%	1.075	107.61%	-7.61%	-0.125	-41.67%
830	-1	+1	0	-1	-1	16.375	3	0.275	0.96	79.07%	2:44	92.68%	2.25	115.93%	-15.93%	-0.025	-8.33%
832	-2	-2	0	-2	-2	17	2	0.150	0.51	41.54%	3:53	65.24%	2.875	120.35%	-20.35%	-0.150	-50.00%
834	+1	+1	0	-1	-1	14.375	3.25	0.275	1.10	90.07%	2:29	102.01%	0.25	101.77%	-1.77%	-0.025	-8.33%
837	-2	-2	0	-2	-2	16.3	4	0.375	1.32	108.32%	3:06	81.72%	2.175	115.40%	-15.40%	0.075	25.00%
841	-2	-1	0	-2	-2	15	4	0.350	1.34	109.86%	2:28	102.70%	0.875	106.19%	-6.19%	0.050	16.67%
842	-2	-1	+1	-2	-2	15.75	3	0.200	0.73	59.79%	2:36	97.44%	1.625	111.50%	-11.50%	-0.100	-33.33%
849	+2	+2	+2	+2	+2	15.375	5	0.550	2.05	168.43%	2:14	113.43%	1.25	108.85%	-8.85%	0.250	83.33%
850	-1	-1	+1	-1	-1	15.375	4	0.350	1.30	107.18%	2:27	103.40%	1.25	108.85%	-8.85%	0.050	16.67%
851	-1	-2	+1	-1	-1	13.5	3.5	0.300	1.27	104.63%	2:01	125.62%	-0.625	95.58%	4.42%	0.000	0.00%
855	-1	-1	+2	-1	+1	14.1	5.5	0.550	2.24	183.67%	2:24	105.56%	-0.025	99.82%	0.18%	0.250	83.33%
856	-2	-2	+1	-1	-1	13.25	2.5	0.175	0.76	62.18%	2:16	111.76%	-0.875	93.81%	6.19%	-0.125	-41.67%
857	-3	-2	+1	-1	-2	12.3	3	0.200	0.93	76.56%	2:38	96.20%	-1.825	87.08%	12.92%	-0.100	-33.33%
858	-1	+1	+1	+1	+1	13.875	4.5	0.375	1.55	127.25%	2:40	95.00%	-0.25	98.23%	1.77%	0.075	25.00%
871	-1	+1	+1	+1	+1	13.4	4.5	0.350	1.50	122.98%	2:40	95.00%	-0.725	94.87%	5.13%	0.050	16.67%
878	+3	+2	+1	+2	+2	14.375	5	0.500	1.99	163.77%	2:20	108.57%	0.25	101.77%	-1.77%	0.200	66.67%

TABLE C-2. Rationalized Hurvich-Jameson Hue Test Data Table.

TRANSFORMATION ENERGY VALUES				TOTAL ENERGY		DOMINANTS DOMAIN	RATIONALIZED HUE ENERGY				HUE RECEPTOR FIELD ENERGIES			
$\int X(\lambda)$	$\int Y(\lambda)$	$\int Z(\lambda)$	$\int S(\lambda)$	$\int X+\int Y+\int Z$	% of Total of Normal Light Available	X Y Z	R	G	B	Y	R-G	B-G	B-R	B-Y
106.8535	106.8535	106.856	97.06964	320.56	100.00%	N	444.43	444.40	444.51	444.38	0.03	0.11	0.08	0.13
71.361	53.696	39.36	28.837	164.42	51.29%	X	439.02	428.14	573.59	436.50	10.88	145.45	134.57	137.09
93.018	94.417	79.986	81.000	267.42	83.42%	X	470.57	471.04	462.55	471.40	-0.47	-8.50	-8.03	-8.86
85.176	86.593	49.363	63.454	221.13	68.98%	X	521.91	522.44	509.33	524.28	-0.53	-13.11	-12.58	-14.95
77.692	80.613	9.5394	41.895	167.84	52.36%	X	639.83	641.33	606.42	645.91	-1.50	-34.91	-33.41	-39.49
77.202	77.066	5.0807	32.639	159.35	49.71%	X	644.90	644.55	633.99	650.74	0.35	-10.56	-10.92	-16.76
75.704	69.009	2.2874	22.972	147.00	45.86%	X	627.48	622.63	673.42	631.84	4.85	50.79	45.94	41.57
78.299	77.547	17.352	42.163	173.20	54.03%	X	597.15	596.50	593.46	601.51	0.65	-3.04	-3.69	-8.04
70.75	58.705	22.96	28.706	152.42	47.55%	X	516.20	508.09	610.64	516.56	8.10	102.55	94.44	94.08
71.234	54.714	4.6649	11.553	130.61	40.74%	X	562.77	549.82	713.67	563.49	12.96	163.86	150.90	150.18
57.193	40.525	0.27609	8.2646	97.99	30.57%	X	557.09	539.73	762.78	556.70	17.36	223.06	205.70	206.09
54.153	35.07	1.1407	5.527	90.36	28.19%	X	524.52	503.05	783.49	522.29	21.48	280.44	258.96	261.20
39.908	21.992	2.5425	2.5534	64.44	20.10%	X	464.30	436.13	810.34	458.85	28.16	374.21	346.05	351.49
40.573	21.984	3.1758	2.176	65.73	20.51%	X	455.36	426.73	807.91	449.55	28.64	381.19	352.55	358.37
83.41	70.076	75.836	56.691	229.32	71.54%	N	409.36	403.50	484.16	407.02	5.86	80.66	74.80	77.13
70.24	49.638	50.02	29.185	169.90	53.00%	N	393.58	381.35	548.14	389.42	12.23	166.79	154.56	158.72
71.05271	50.30458	47.94573	28.27336	169.30	52.81%	N	400.24	387.88	556.01	396.25	12.37	168.13	155.77	159.76
62.2782	39.90385	46.52715	24.15316	148.71	46.39%	N	362.77	347.63	555.65	357.08	15.14	208.01	192.87	198.57
30.79741	13.92795	14.18329	4.277275	58.91	18.38%	N	324.77	295.93	689.64	315.03	28.84	393.71	364.87	374.61
72.39307	55.6429	62.19472	41.70339	190.23	59.34%	N	392.92	384.05	506.05	389.46	8.87	122.00	113.13	116.60
26.51911	11.67248	19.60959	6.169637	57.80	18.03%	N	277.78	251.99	608.63	267.29	25.80	356.65	330.85	341.34
27.62207	21.24305	67.54947	39.88193	116.41	36.32%	Z	245.08	239.75	325.58	237.97	5.33	85.83	80.50	87.61
35.43412	30.50331	74.02576	47.98977	139.96	43.66%	Z	291.72	288.31	344.98	286.40	3.40	56.67	53.26	58.57
59.38214	66.44376	93.23339	79.62954	219.06	68.34%	Z	403.32	406.60	365.62	402.75	-3.28	-40.98	-37.70	-37.13
25.48951	29.87695	82.04311	56.22988	137.41	42.87%	Z	288.79	292.18	258.37	284.84	-3.39	-33.82	-30.43	-26.47
17.02956	17.92332	64.36384	40.50778	99.32	30.98%	Z	240.26	241.39	241.39	234.39	-1.13	0.00	1.13	7.01
43.45711	51.5019	85.65346	70.7298	180.61	56.34%	Z	378.69	383.25	327.11	377.65	-4.56	-56.14	-51.58	-50.55
12.76826	13.944	62.34597	40.68619	89.06	27.78%	Z	208.26	209.85	206.06	201.53	-1.59	-3.79	-2.19	4.54
13.05969	10.99612	63.76162	34.10901	87.82	27.39%	Z	167.67	165.60	213.74	158.95	2.07	48.15	46.08	54.80
15.9703	22.1464	66.58706	50.59914	104.70	32.66%	Z	280.00	286.14	216.32	276.37	-6.14	-69.82	-63.68	-60.05
11.63591	30.06057	10.03344	32.15666	51.73	16.14%	X	762.97	798.58	299.13	779.97	-35.60	-499.45	-463.84	-480.84
32.22522	54.40923	10.00419	41.13046	96.64	30.15%	X	743.08	765.91	438.54	756.77	-22.83	-327.37	-304.54	-318.23

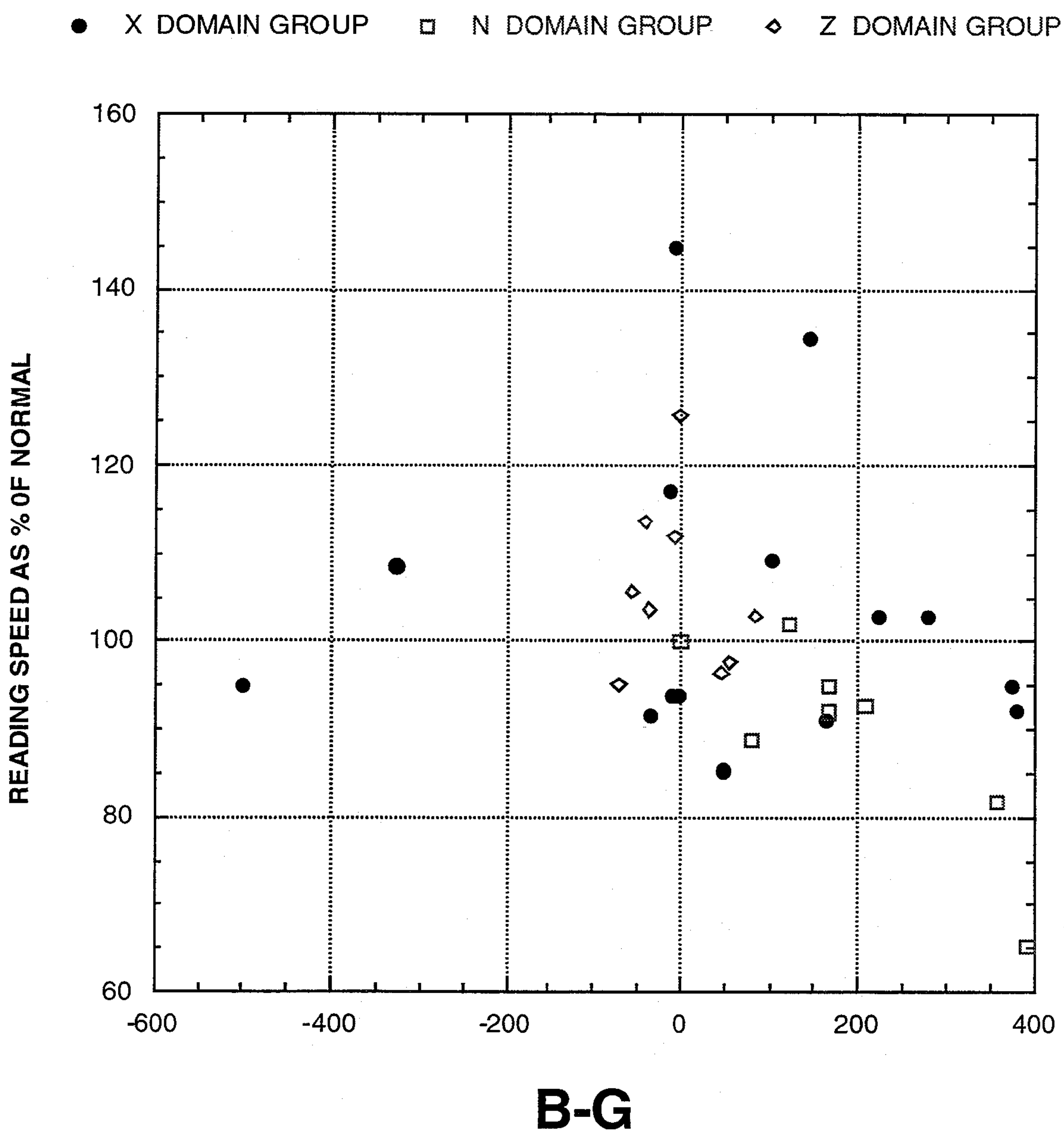

FIGURE C-1. Rationalized B-G Hue Receptor Field Energy vs. Reading Speed.

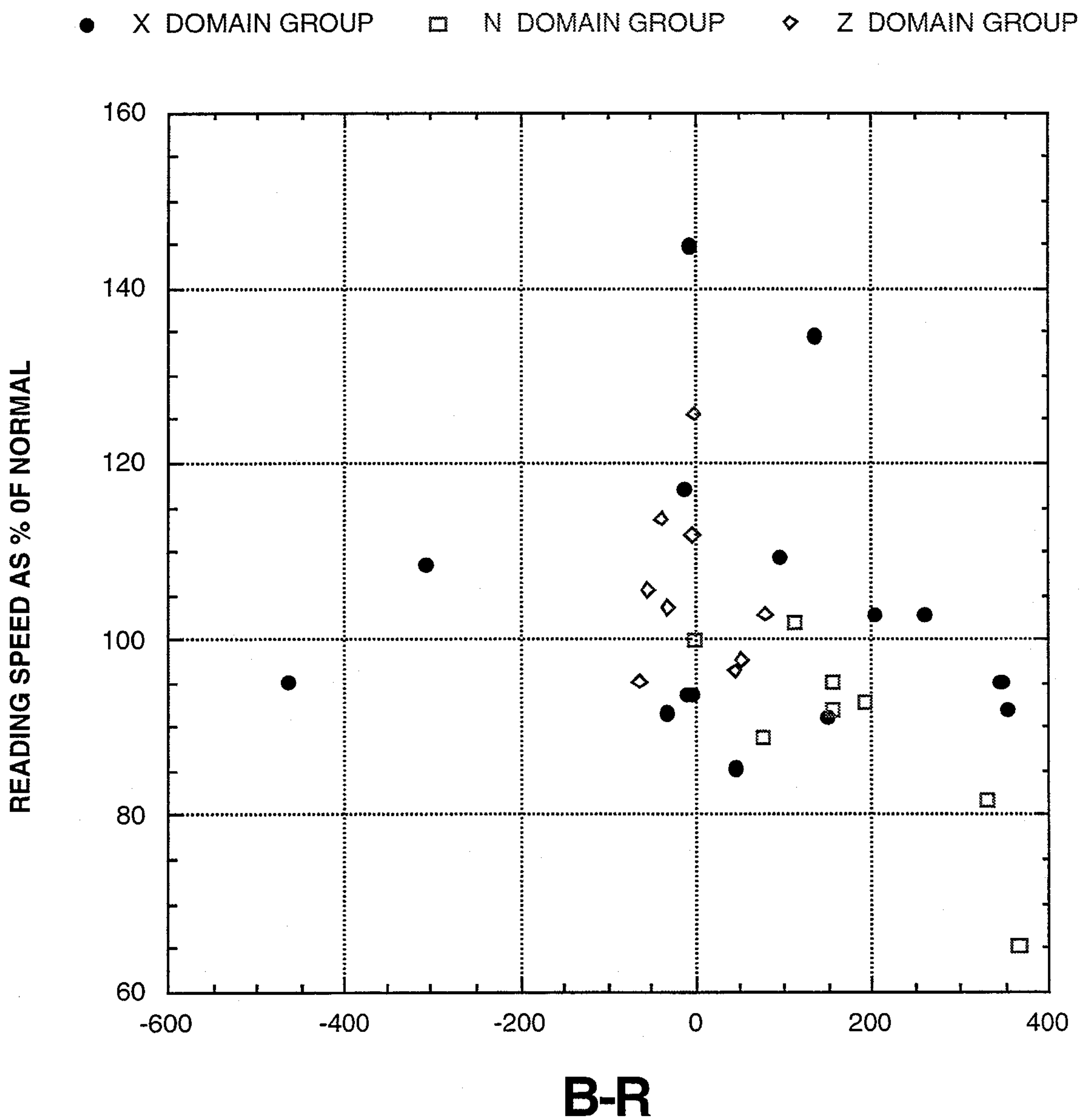

FIGURE C-2. Rationalized B-R Hue Receptor Field Energy vs. Reading Speed.

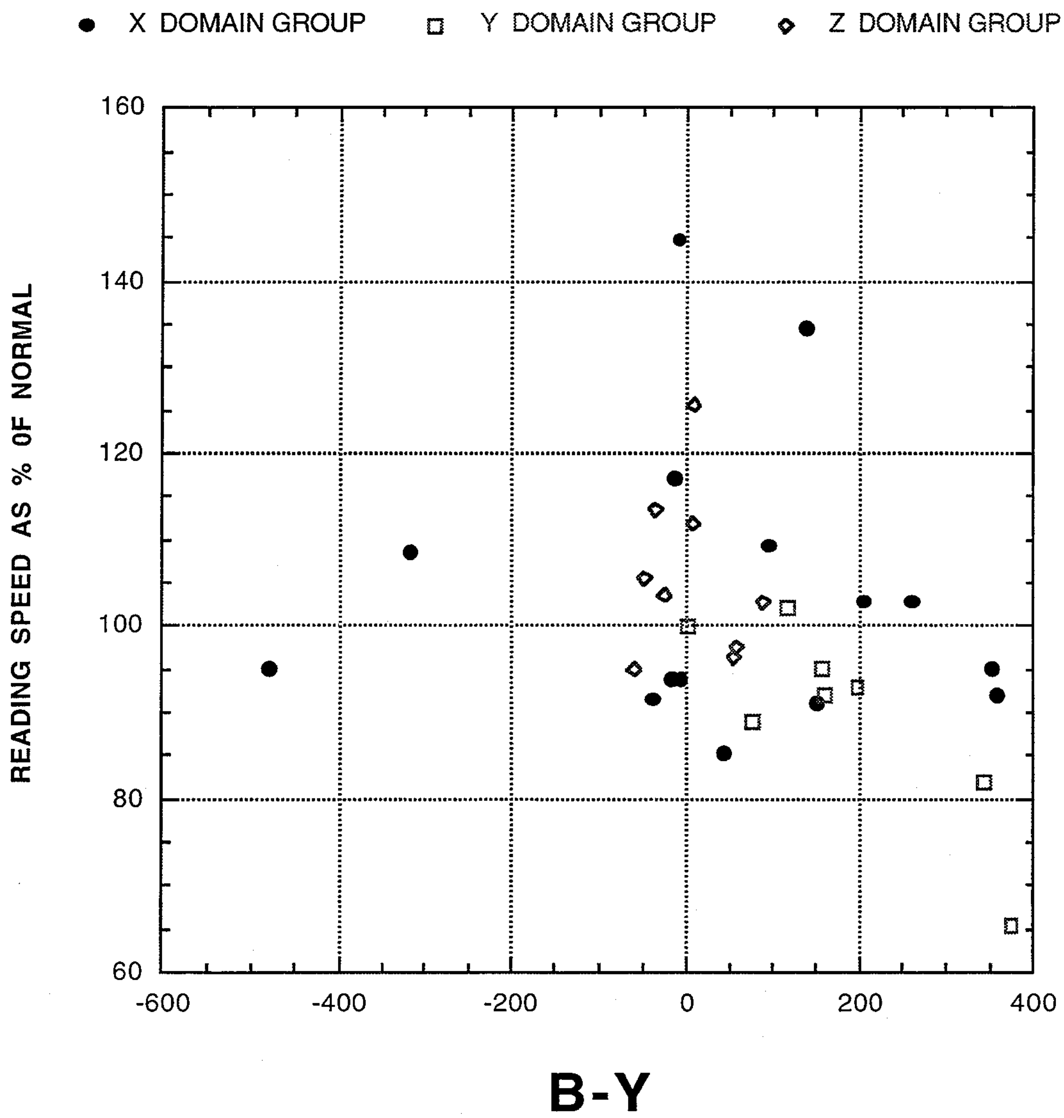

FIGURE C-3. Rationalized B-Y Hue Receptor Field Energy vs. Reading Speed.

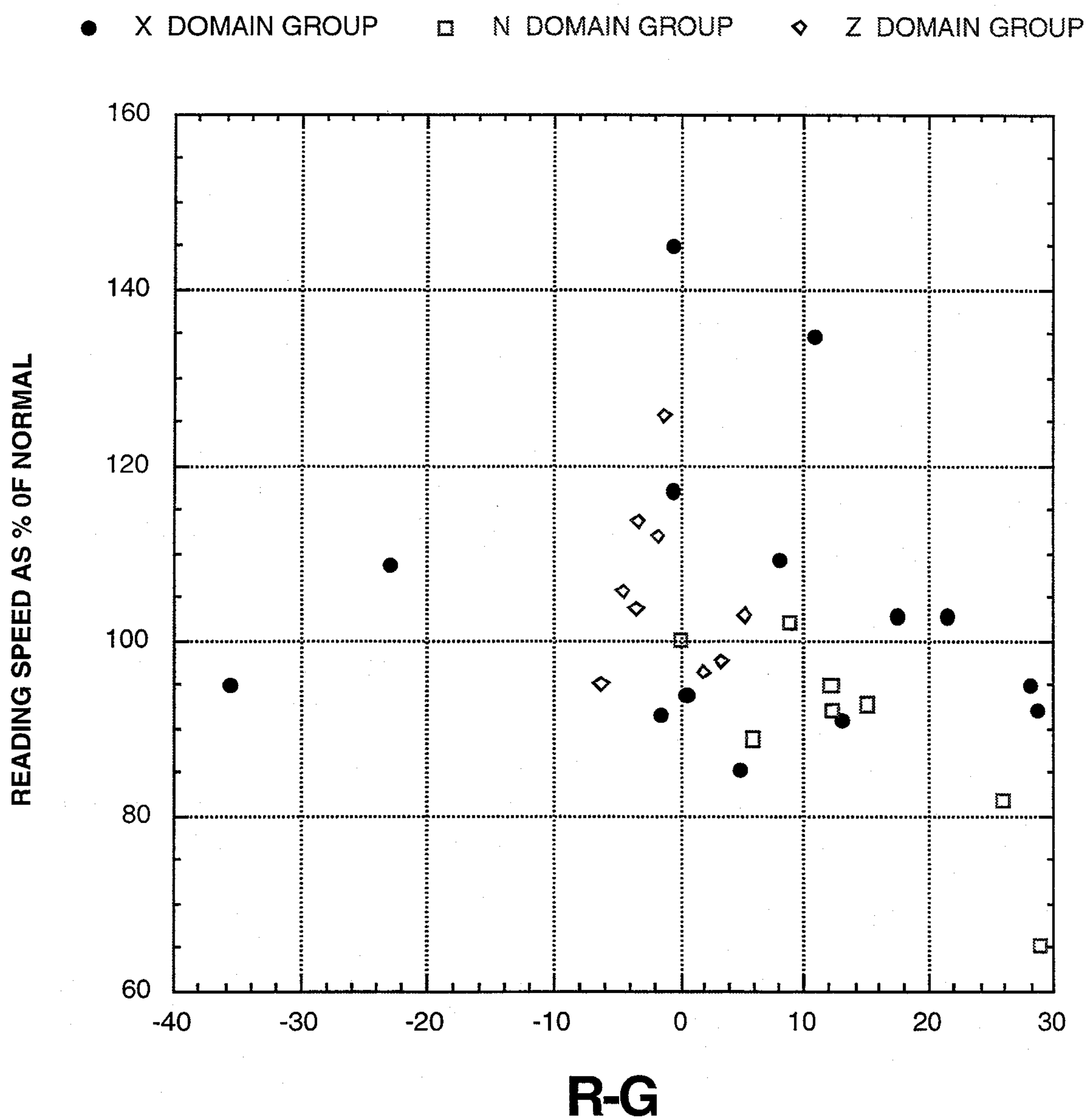

FIGURE C-4. Rationalized R-G Hue Receptor Field Energy vs. Reading Speed.

If one looks at this set of graphs, one notices three things:

1. All four plots have pattern similarity (in the formal mathematical sense of the term).

2. These plots represent a proportionalized pattern similarity, with only the scale factor of the horizontal being different.

3. This pattern is familiar. It is the pattern of the rationalized $\mathcal{R}$-$\mathcal{G}$ data plot presented as Figure 48 in the main body of this report.

The implications of these two pattern similarities, to the Hurvich-Jameson equation set, are somewhat formidable.

The Hurvich-Jameson theory was evolved in the days before the discovery of receptor fields and the subsequent development of the receptor field theory of human vision, and, in fact, predates it by some 30 years. The Hurvich-Jameson theory bases its model on a two-color channel model, an R-G channel, and B-Y channel. We know today (under the modern receptor field theory of human vision) that there are four field channels as opposed to the Hurvich-Jameson model's two. Yet we know that the Hurvich-Jameson equations work and have been tested and used by the scientific community to analyze color vision for nearly half a century.

The reason for this lies in the nature of mathematics used by Hurvich and Jameson and its relationship to the real world structure of the eye. Hurvich and Jameson were able, through advanced mathematics, to derive a set of equations that resolved all four receptor fields into a single receptor field's form and then to use it to deduce the collective operation of the eye. That they were able to do this in the days before modern computer calculation capability is a tribute to their mathematical skill and the sophistication of their method.

This was permitted because the original Hurvich and Jameson experimental data were taken on a “normal color vision population” where there is no significant spectral sensitivity (as there is in the group we are studying). Under such conditions, there would be no variation in performance factors and the field channel plots would be straight lines. Since R-G and B-Y intersect at essentially right angles, this means the human vision system would be reduced to a single mathematical unity for any given spectral frequency input.

In theory, the real B-G and B-R receptor field inputs ought to perturb the B-Y channel value; however, as a result of the scaling factors involved in the equation set, this perturbation works out to be 1% to 1.5% and since the B-G and B-R receptor field inputs are not always of the same sign, the error caused by them is often further reduced by cancellation, to the point where the perturbation lies within the bounds of experimental error on a human factors

test. This is probably why the scaling factors evolved that way. The result is that the Hurvich-Jameson equation set is able to represent normal human color vision as a mathematical unity in a two-dimensional array within the limits of experimental error—even though there are actually four receptor field variables.

Some points of interest are worth noting in regard to the above findings:

1. Since the Hurvich-Jameson equation set reduces the vision performance pattern to a single R-G form and minimizes all other perturbations to within the limit of experimental error, it is unable to be used to evaluate the receptor field performance dependence of Irlen type dyslexics. Using this technique would result in deciding that the test subject has "normal" color vision within several receptor fields where he does not. Using this technique would probably (and does in this case) give a false estimate of the source and nature of the problem.

2. The previously discussed condition represents an interesting exercise in the problems of the use of experimental mathematics in reducing data to form a valid working model that does not conform to physical reality.

3. After Hurvich and Jameson produced their theory of color vision, a number of different investigations produced a number of similar equation sets (differing mainly in their constant sets) that appear to explain color vision differently from the Hurvich and Jameson set, but still give useful and correlatable results. Such equation sets have on several occasions been used to propagate "alternate theories of human color vision."

One possibility that would explain this embarrassment of riches is presented as a result of this experiment. In theory, if Hurvich and Jameson can produce an equation set that produces mathematical unity based on the R-G receptor field, someone else should in theory be able to build a similar model based on each of the other three receptor fields and have them reflect reality as well. In fact, depending on how one chooses to handle the scaling factors and weigh and average out the perturbation of the other field, one could conceivably come up with more than three sets of equations that function within the limits of detectable visual phenomena. In short, they may be substantially valid and merely reflecting physical reality from a different mathematical perspective.

In this regard, it would be interesting to check some of these other equation sets with data from Irlen-type dyslexics to see if they form constant single receptor field model plots. (This has not been done as part of this effort because of the time and effort involved, but it would be an interesting exercise.)

4. One interesting possibility raised by the previously described analysis is that since the color vision system performance of Irlen-type dyslexia does vary with spectral frequency, this attribute could be used as an experimental technique to develop a better understanding of the nature of human vision as a whole.

Appendix D
POSSIBLE PHYSICAL CAUSES FOR THE IRLEN EFFECT: A DISCUSSION

PHYSICAL CAUSES HYPOTHESES

One of the questions that is worth pondering is why the Irlen effect occurs in certain individuals as opposed to the "normal" population. If one adopts the position that the Irlen effect is the result of a "vision problem," one can propose a number of possible hypotheses that could cause or account for this sort of phenomenon. Most of these candidates are already known to exist in some people or have been hypothesized as existing in people as a result of studies of abnormal color vision. Though, in many cases, the phenomenon described has been difficult to prove and its existence remains a hypothesis.[66] In short, the following list of possible causes is not all that original, while in the color vision field, gross defects producing abnormal color vision are what is being addressed. One could easily hypothesize that a marginal or partial variant of any of these conditions could result in a color vision processing problem resulting in an Irlen-type effect. Or more likely, since there are several such distinct groups of Irlen-type affected people in the population, the collective result of several of these phenomena grouped in some interrelated manner form the basis of the distinct characteristic exhibited by the various individual Irlen subgroups.

The various identified physical causes hypothesized are listed below for the sake of discussion.

OUTER EYE PROBLEMS

Low Albumen in the Lens of the Eye

The lens of the eye contains a substance known as albumen, which absorbs ultraviolet light. It is known that concentrations of albumen in the lens vary significantly between individuals, by as much as a factor 10 or 20 or more.[67] The concentration of albumens in the lens significantly affects an individual's ability to see in the short wavelengths[68]. It is known that Aphakic subjects, people without lenses (surgically removed), can see in the ultraviolet region (to as low as 302 nm), a phenomenon that was extensively studied in France in mid-century.[69]

This means that the eye's receptor system is capable of processing low-end ultraviolet light, if it reaches the system.

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[66] Falk, p. 277.
[67] Le Grand, pp. 91-92.
[68] Le Grand, p. 89.
[69] Le Grand, p. 94.

In point of fact, the French data show that not only is this true but that ultraviolet light is capable of affecting the vision system all the way up to the green cones[70] activation region, which means that the ultraviolet energy is capable of affecting the blue cones, the green cones, and the red cone receptor dyes. The French data, in fact, show that Aphakics exposed to ultraviolet light in the 300-mm to 360-mm range perceive the image as blue at a wavelength of 453 mm, with some variation between individual Aphakics being reported.[71]

It can be hypothesized that individuals with the Irlen phenomenon have very low albumen in the eye lenses (or the albumen which is actually made up of a series of ultraviolet-absorbing dyes has some of the individual dyes missing, leaving holes in the ultraviolet spectral protection of the eye) and see into the ultraviolet spectrum. The presence of the ultraviolet light affects their eye's receptor ability to process information in some manner. This hypothesis is supported by the fact that ultraviolet filters significantly help some people suffering from the Irlen effect.

Since the concentration of albumen increases moderately with age to really high levels, one would therefore expect under this hypothesis that the Irlen effect would go away with age. This does not appear to be the case.

High Albumen in the Lens of the Eye

It can also be hypothesized that people with the Irlen phenomenon have a higher than normal concentration of albumens in the lens of the eye, which reduces the presence of short-end radiation to the eye receptors, which debalances the eye's processing of information in some manner. Under this hypothesis, the function of Irlen filters would be to rebalance (turn) the rest of the eye's receptor system to provide "normal" processing of the image that the eye is seeing. As the concentration of albumens increases moderately with age to a reasonably high level, one would therefore expect under this hypothesis that the Irlen effect would show up more in older people. This does not appear to be the case.

[70] Le Grand, p. 93.
[71] Le Grand, p. 94.

RETINA PROBLEMS

Missing Macula Lutea

Near the center of the eye's retina is a region called the Fovea, which contains vast numbers of receptor cones. This high-cone area is covered with a yellow pigment area called the Macula Lutea, which absorbs much of the blue light that reaches the area.[72] If the Macula Lutea were weak or missing, the blue frequency light could reach the cone system beneath and influence it in a manner that causes subsequent image processing problems. Since this is the region of maximum cone concentration, this would have a disproportional effect on the color vision system.

High Macula Lutea

If the Macula Lutea yellow dye concentration were significantly higher than normal, this would cause a shifting of the color responses in the high cone density area of the Fovea. Such a shift might be sufficient to not only affect color perception generally, but since the Fovea cones would then see a different color set than the cones in the non-Fovea, the shift might set up a processing problem.

Non Standard Macula Lutea

The yellow dye of the Macula Lutea is in all likelihood a composite dye system like the albumen dye of the lens. (A supposition on which there is no data for the Macula Lutea but which is known to be true in the case of albumen.) It could be hypothesized that some of the Macula Lutea constituents are missing, producing holes in the dye frequency absorption spectra, causing an abnormal response in the cones below the Macula Lutea, which presents a processing problem for the vision system, which manifests itself as the Irlen effect.

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[72] Falk, p. 150.

Low Epithelium Pigment

The normal eye contains a layer of cells called Epitheliums in which the receptor cells are embedded. These Epithelium cells contain an organic dye or pigment whose function is to prevent light passing through one receptor cell from reaching the one next to it by absorbing the light as is passes through the surrounding Epithelium cells.[73] It is possible that, in individuals subject to the Irlen phenomenon, the concentration of Epithelium pigment dye is unusually low or missing and that, as a result, light affecting one receptor passes through and effects other near by receptors, perhaps, even with its spectral signature modified by passing through the first receptor cell and intervening Epithelium pigment. In this case, the eye is having difficulty processing the resulting abnormal interference signature data. This hypothesis would certainly explain why some people with the Irlen effect are sensitive to glare, have difficulty with light of high angles of obliquity, complain about diffused light, and like to read in and read better in dim light.

RECEPTOR ABNORMALITIES

One can also propose a number of hypotheses involving the eye's receptor location and distribution to account for the Irlen phenomena. These include the following:

Abnormal Receptor Distribution

Normally cones and rods are spread out in a relatively stable statistical pattern. It is entirely possible that in individuals who experience the Irlen phenomena that this pattern is not normal in one or more of its statistical attributes.

Proportional Distribution. Normally red, green, and blue cones are present in the eye in a relatively fixed percentage ratio, as is the ratio between cones and rods.[74] This ratio of distribution may not be the standard normal in people experiencing the Irlen phenomena. The ratio may not be sufficiently abnormal to register as a form of color blindness but still sufficiently abnormal so that the brain cannot process the data in a "normal" manner and must devote additional effort to processing and analyzing the input signals. Through years of individual brain accommodations, the individual's brain has mostly successfully adapted to this ratio problem and it is mostly unnoticeable to him or her. While the individual would think he or she sees and processes visual data normally, this would not be the case. And seeing on the part of this individual does take

[73] Le Grand, pp. 399 and 361-362.
[74] Widdel, p. 19.

additional abnormal effort to process the visual stimuli, which in the end, produces the Irlen effect.

Angular Distribution of System. Normal human eyes have their cones organized in a reasonably set concentric pattern,[75] which is manifested as an angularity in color perception in human vision. It is possible in people who exhibit the Irlen effect, that the zones of distribution of color receptors are abnormal, either more dispersed or narrower than normal, causing single processing problems in the brain.

Abnormal Cone Distribution Over the Retina Surface. Normally, significant cone vision is confined to a small region of the retina's surface called the Fovea, a zone of the retina where the cone concentration is about 30 times higher than on the rest of the retina surface[76]. If the cone receptors were spread out more widely into the rest of the retina, which normally contains mainly rods, this would present a significant processing problem to the brain. This hypothesis is supported by the fact that a number of people who suffer from the Irlen effect report problems handling glare and light coming in at high angles of obliquity (a phenomena that they may try to accommodate for by shading their eyes from incoming side light when reading, a reaction known to occur in some people who suffer from the Irlen effect).

On the other hand, the outer surface of the retina normally has only (5%) of the cone density of the Fovea,[77] which gives normal people poor peripheral color vision.[78] If these peripheral cone concentrations were larger than normal, people with this condition would have moderately better than normal peripheral color vision, which would fit some of the symptomalogy of people reporting the Irlen effect. However this better than normal peripheral color vision might also cause a processing problem to the brain.

One or more of these receptor distribution conditions could occur simultaneously, presenting an abnormal signal output from the eye, which could give the brain a signal processing problem. This would show up as a reading and vision problem, below the limit of detectability of normal commercial eye exams, but still affecting the individual's ability to perform. In most cases the individual has adopted to the "abnormal vision" sufficiently to be reasonable functional and believes his or her vision is "normal" in the sense that he or she thinks everyone sees the same way he or she does.

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[75] Woodson, p. 24.
[76] Falk, p. 153.
[77] Falk, p. 153.
[78] Falk, p. 155.

RECEPTOR LOCATIONS

The visual receptors, both cones and rods, are normally imbedded flush in a layer of Epithelium-containing cells, meant to shield them from excess angled light and mutual interferences.[79] If the receptors were displaced vertically from their normal essentially flush state, one could hypothesize an Irlen effect causing conditions such as:

Protruding Receptors

If the receptors protrude above the Epithelium cell surface, one would expect the following:

1. High sensitivity to side or high oblique angle light
2. Increased sensitivity to light in general
3. Interferences and interactions between individual receptors as the light passes through them and interacts.

These are all conditions that are either reported or can be inferred from symptoms reported by people suffering from the Irlen phenomenon.

Recessed Receptors

If the receptors were recessed below the Epithelium cell surface one would expect the following:

1. A narrow angle of focus with poorer peripheral vision
2. A liking for high perpendicularity of light
3. A liking for, and a higher tolerance to, a higher level of light generally.

All of which have been reported by some sub groups of the population of individuals suffering from the Irlen effect.

Non-Uniformly Embedded Receptors

Since there are four independent types of receptors, it is conceivable that the above abnormal conditions might appear in some, or all of the four receptor types independently of each other. This in turn opens the possibility that only one set of receptor cones protrude or is recessed, and producing a signal that

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[79] Le Grand, p. 359.

is at variance with the rest and that the brain is having difficulty processing this in a normal manner.

RECEPTOR SIGNAL-PROCESSING PROBLEMS

A number of possible malfunctions of the receptor mechanism can also be hypothesized as the causing agent of the Irlen effect. These include the following:

Low Dye Concentrations in the Receptors

This would cause abnormal low cone responses to color stimuli, which would make processing color vision responses abnormal and could cause the brain a processing problem. This processing problem would be more pronounced if the dye of only one color cone system were abnormally low.

The more interesting possibility, however, is a low dye concentration in the rods. This could have the effect of raising the cut-off point for rod vision, which would result in the Duplex Theory of Visual Function (of rods not entering into color vision[80]) not being valid for the people at the higher threshold level. This could account for the glare and blinking problems reported by some individuals with the Irlen phenomenon. These symptoms are in many ways very similar to the reported symptoms of a total achromat. See the account of the noted Norwegian achromat researcher Knot Nordby of his own physical reactions to high light amounts[81] in Hess, pp. 290-315.

High Dye Concentration in Receptors

High dye concentration in the receptor could cause higher than normal signal response in the cones, which could cause a distortion in processing color spectrum data. This processing problem would be more pronounced if the dye of only one color cone system were abnormally high.

Abnormal Dye Frequency Response

From work in gross color defect vision, we know that certain mutant color response dyes can developed in certain individuals.[82] These mutant dyes have a slightly different color frequency response than normal. In fact, recent work by

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[80] Falk, pp. 279-280 and Hess, pp. 3-6.
[81] Hess, pp. 309-312.
[82] Nathans, pp. 42-49.

Jeremy Nathans of Johns Hopkins University School of Medicine has shown that anomalous trichromats color vision is the result of defects in red and green dyes in the cones, and that this color variance is the direct result of a mutation of the pigment-producing gene on the X chromosome.[83] In fact, these data would suggest that there are several individual frequency dye compounds can exist in the human eye, depending on the degree of homogeneous recombination distributions in the green pigment gene in people. This condition is believed to exists in at least 8% of the male population and 1% of the female population.[84] Individuals with Irlen effect vision could have this sort of mutant dye in one or more receptors vision elements, resulting in abnormal color and color processing.

A more complicated scenario could also be proposed, in which the receptor of one class of cones could produce both some cones with the normal dye and some cones with one or more of the mutant dyes in its family, or even perhaps in the same cone. This would result in a spread out or the generation of multiple response curves for that receptor in the vision system. This could easily result in a processing problem for the brain, particularly with the more complex scenario. It might also be a phenomena that is very hard to isolate from the result of normal color vision tests, because the normal peaks that we expect and are looking for in these types of test would be there. Since the tests do not look at the whole signal spectrum, it probably does not find them unless they are dominant.

At the preset time, only the variation of the green cone dye has been investigated and identified, but that does not rule out the prospects of similar dye variants in the others cones.

High or Low Signal Pulse Generation

It is conceivable that the dye system of the cones is all right, but the nerve amplifiers at the base of the cone produces an abnormal signal, either stronger or weaker than "normal" and that the vision system has difficulty processing this abnormal signal. It is probable that this would have a more disturbing effect if the signal were higher than normal.

[83] Nathans, pp. 42-49.
[84] Nathans, p. 42.

ROD ACTIVITY

High Dye Concentrations. See above.

Low Dye Concentrations. See above.

Failure of Rods to Switch Off

It is generally held that the rods become saturated and turn off before or shortly after the threshold of concentrations of light needed for color vision is reached.[85] This is called the Duplex Theory of Visual Function.[86] The existence of the phenomena in people has been brought into question by modern night vision studies,[87] as has the existence of a fixed shut-off point that is the same in all people. It can be hypothesized that people who exhibit the Irlen phenomenon do not have normal shut-off points for rod vision, or perhaps the onset of cone vision threshold is lower and that, as a result, the rods remain active in the vision system of these people, resulting in some overlap in the operation of the two vision systems, resulting in interferences and abnormal effects in the vision data processing option of the individual.

Rod Desensitization Failure

According to modern physiological theory, the rod vision system is shut down as a result of rapid growth in the signal rather then saturation of the dye system. In this way, the rod vision signaling switch is held to act in the manner of a high pass temporal and spatial filter (automatic gain controlling and subtracting filtering) in a modern electrical circuit.[88] If this self-limiting switch in the rod were to fail or be off from its nominal sensitivity, it is conceivable that the rod system would still be functioning in the cone vision range, resulting in interference and visual data processing problems. This would be particularly severe if the outer eye's ultraviolet absorbing pigment of the lens were on the low side, resulting in higher than normally ultraviolet sensitivity in the rod system.

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[85] Hess, p. 101.
[86] Hess, pp. 3-6.
[87] Chess, pp. 103-123.
[88] Hess pp. 102 & 122, and Hubel, pp. 47-49.

RECEPTOR SIGNAL INTERACTION

Misconnected Receptors

It has been hypothesized in the study of people with abnormal color vision that one of the possible problems is that some cones of one color are attached to the nerve systems supporting the cones of another color[89] such as blue cones attached to green reporting nerves). Since color signals are believed to be a sum of the collected output of a number of sensor cone or rod cells,[90], [91] this misplacement would result in a confusing cross-talk signal that might cause processing problems. If this were to occur on a significant level it might produce the Irlen effect.

Cross-talk

The zone just below the receptor cells in the eye contains an assortment of specialized nerve cells whose function we do not understand. It is, however, highly possible that if these cells were misconnected in some manner that the various classes of receptors could cross-talk to each other, resulting in a signal-processing problem. This in turn could produce the Irlen effect.

RECEPTOR FIELD ABNORMALITIES

Under the Hering, Jameson-Hurvich, Zrenner receptor field theory of color vision, one can postulate a large number of causes that might upset the timing balance of the receptor fields and therefore account for Scotopic Sensitivity Syndrome and the Irlen effect's modification of it. These causes include

1. All of the receptor location problems proposed previously.
2. All of the receptor signal processing problems discussed previously. (Abnormal dye frequency could play havoc with receptor field's timing control circuit.)
3. Misconnected receptor circuitry, which in this configuration the changes are quite high.

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[89] Falk, p. 279.
[90] This is more or less a certainty, since there are 7×10^6 cones and 110 to 130×10^6 rods for a total of only 800,000 optical nerve fibers (Le Grand, p. 364).
[91] See discussion of neural pathway theory in Widdel, p. 104 to 108.

While any or all of these receptor conditions wired into a Zrenner or De Monasterio-type receptor field configuration could account for the problem, the receptor field theory also contains four other unique options. These are described in the following paragraphs.

ZONE IMBALANCE

The Zrenner-De Monasterio receptor field theory postulates basically two balanced concentric zones of cones of differing composition. If these zones were not balanced in an individual, this could result in a timing-signal problem that could manifest itself as Scotopic Sensitivity Syndrome. (By shifting the frequency spectrum coming into the eye, one could rebalance the system and bring it back into equilibrium. This would account for the Irlen effect.)

ABNORMAL PROPORTIONALITY OF RECEPTOR FIELDS

Both the Zrenner and De Monasterio receptor field theories postulate a yellow field composed of red and green cones mixed in some ratio. If this ratio were incorrect and/or skewed in some manner; this could result in a timing signal problem that could manifest itself as Scotopic Sensitivity Syndrome. (By shifting the frequency spectrum coming into the eye, one could rebalance the system and bring it back into equilibrium. This would account for the Irlen effect.)

RECEPTOR FIELD COMPOSITION

Under the receptor field theory, the two zonal fields are made of balanced homogeneous (of precisely internally balanced) zonal fields. If the composition of these fields was not homogenize because of misplaced cone types or a mutant dye variant in some of the cones, this could alter the timing signal and could thereby result in a timing-signal problem in the brain's processing that manifests itself as Scotopic Sensitivity Syndrome. (By shifting the frequency spectrum coming into the eye, one could rebalance the system and bring it back into equilibrium. This would account for the Irlen effect.)

MISALLOCATED RECEPTOR FIELD SYSTEM

It can be postulated that total color vision is made up of the processed sum of a number of different types of receptor fields. If some types of receptor fields were missing or if they were available in the wrong ratio in the eye of a given individual, the brain might have difficulty processing the total image set. This in turn could result in the Scotopic Sensitivity Syndrome condition.

NOTE ON RECEPTOR FIELD THEORY CAUSE ANALYSES

Isolating a single cause for Scotopic Sensitivity Syndrome based on receptor field theory is likely to be quite difficult as a result of two facts:

1. The nature, composition, and operation of receptor fields in humans is not well understood. (In fact there is still some question as to its validity.)

2. If the problem is merely a ratio of good receptors in the fields in some manner, at our present state of the art in instrumentation and methodology for color vision analyses, we have no way of finding and analyzing it.

OPTIC NERVE SCRAMBLE

We can hypothesize that the eye itself is normal in its function and that the optic nerve is misconnected internally, resulting in cross-talk and processing problems in the receiving portions of the brain.

DEEP-BRAIN VISION-PROCESSING PROBLEMS

The two hypothetical scenarios for causing deep-brain processing problems of the vision signal that could result in the Irlen effect are

1. The eye is producing an abnormal signal that the normal processing system of the brain is having trouble handling and compensating for, as a result of the complexity of the processing required.

2. Eye signal is normal but the vision-processing system in the brain is abnormally and misprocesses it in some way.

DEEP-BRAIN PROCESSING

The vast majority of the scientific and psychological commentary hold that dyslexia is not a vision problem and that it results from a deep-brain information-processing problem and that the Irlen effect does not exist or is at most, merely a symptom or manifestation of this primary deep-brain processing problem.

DISCUSSION OF HYPOTHESES IN LIGHT OF TEST RESULTS

QUESTIONS

The questions that one would wish to discuss are as follows:

1. Could any of these "physical cause hypotheses" account for the Irlen effect phenomenon in people?

2. Is there some related subset of these that, if they were to occur simultaneously and interrelate as mutually dependent variables in an individual could account for the Irlen effect phenomenon in people?

3. Do any data derived from the present experiment tend to

   a. Identify one of these phenomena as a primary player in causing the Irlen effect?

   b. Identify a subset or group of these phenomena as possible candidates for causing the Irlen effect?

   c. Eliminate any of the phenomena as the cause of the Irlen effect?

DISCUSSION OF CAUSES FOR DYSLEXIA

The easiest of the above questions to answer is, What can we eliminate as a possible cause of the Irlen effect as a result of the experiments findings? The answer is, not much. Most of the potential causes are still viable.

We can conclude that the outer eye problems are the least likely candidates though still possible.

Most of the rod activity and interference hypotheses do not appear to be supported by these data. This may be through the result of limitations of the analysis methodology rather than actuality. Considerable anecdotal evidence from the other Irlen subgroups indicates that rod activity intrusion may be a player. Therefore it can not be entirely eliminated based on this one set of

experiments. To determine if rod activity is really a player in this phenomenon, we would need a much more refined and complex test and analysis procedure,[92]. as well as a much larger database, including a representative sample from all the Irlen symptomalogy subgroups. But rod activity does not appear to be a high causal candidate for this individual test subject, based on the current experimental data.

What this experiment has demonstrated is that the most likely causal candidate is a receptor field problem of some sort, be it the result of a physical cause, a signal-processing problem abnormality, or a combination thereof. Almost all of the individual casual candidates' options previously listed are still viable contenders for the primary cause.

This experiment has, however provided new insight into the secondary effects of the basic causes, which manifest themselves as operational problems for the vision-processing system and result in the Irlen effect and perhaps dyslexia in general. These secondary effects are as follows:

Positive and Negative Sign Output Difference From Receptor Fields Produce Different Visual Results

Based on this experimental data, one would be compelled to conclude that positive and negative output signals from the receptor field produce radically different performance in the vision-processing system. This is at variance with generally accepted Receptor Field Theory for normal people, which says that a "mere" changes of sign in receptor field output should not have any visual effect.

Whether this sign changes abnormally is the result of a problem with the ganglia cells at the back of receptor field, a transmission problem in the nerve system carrying the signal, or a processing problem in the vision processing center of the brain in interpreting the signal is not determinable based on this experiment. Only the fact that the signal sign problem is real and is affecting vision processing is determinable from this experiment.

[92] This experiment would have to investigate and try to resolve the following five case possibilities: $(+\mathbf{B}+x\mathbf{r})-(+\mathbf{G}+y\mathbf{r})$; $+\mathbf{B}-(+\mathbf{G}+y\mathbf{r})$; $(+\mathbf{B}+x\mathbf{r})-\mathbf{G}$; $(+\mathbf{B}-\mathbf{G})+x\mathbf{r}$; $(+\mathbf{B}-\mathbf{G})-y\mathbf{r}$ for each of the potential 16 receptor field types. Where **r** is the rod energy exciton energy and x and y are prepositional constants. A sixth case where some receptor fields of a given type are effected by rod intrusion and some are not would also have to be conceded. Though this case might be very hard to get at experimentally/analytically, it could still be a physiological real condition.

Improvement of Vision as a Given Receptor Field Energy Approaches Null From One Side

One of the unexpected findings of this study is that the test subject's vision improved as the energy level in a given receptor field approached zero (or null) from one side but did not pass over the null point and change sign in output for that receptor field system.

This asymptotic effect was not predicted by theory and was unexpected. Therefore the experiment was not set up to investigate it properly. What one would like to do is to look in detail at what exactly happens as one approaches the null asymptote. The experiment's data point set was not finely enough divided to permit this type of detailed inquiry. We are therefore restricted to the previously stated general finding. Without knowing how close is good, versus going too far and falling off the cliff into the bad zone, the result is that we have a general finding for this test subject, without a detailed limit (as one would like).

Again we have only a measured effect, without being able to identify a physiological cause for it, from this experiment.

One Receptor Field Apparent Dominance for a Given Energization Input

It would appear from these data that one given receptor field is dominate in determining the visual performance of the test subject for a given spectral energy range of light energizing the eye.

This domination of one receptor field in determining visual performance for a given spectral energy range was an unexpected phenomena not predicted by theory. This may well represent a unique factor of Irlen type dyslexic vision. At present we cannot be sure of that for the simple reason that to the best of our knowledge no one has ever investigated the question of receptor field dominance in "normal" people. Therefore we do not know for certain that this phenomenon is truly unique to Irlen-type dyslexics (though we can summarize that this is the case).

Again while this may or may not be a processing problem as opposed to a "vision" problem, one cannot determine that as a result from the experimental data in hand.

An Apparent Lack Of Proportional Balance in Response of Receptor Field to Spectral Energy Inputs

Generally the Receptor Field Theory of Vision holds that + B - G receptor fields are balanced by a set of - B + G receptor fields and that this balancing process is repeated for each type of receptor field. This experimental data would indicate that this balance is not there (or is proportionally reduced) for this test subject.

If this is the case, the finding would represent a major new potential physiological cause for Irlen-type dyslexia. (See discussion of this possibility in the main report.) Our problem is again that, while we can discern the effect from the experimental data, we cannot determine the ultimate cause, only an effect. And while the data do fit this theory, there are problems.

The problem with this new theory of primary cause is that while it matches the frequency data of this experiment very well, the theory does not account for quality of light issues that are (anecdotally) widely reported and were not addressed by this experiment. The authors are therefore somewhat leery of proposing it as "the general cause" even though the hypothesis fits the existing experimental test data very well. Though they might be prepared to buy it as part of a multi-factor compound cause, however.

The Various Types of Receptor Fields That Do Not All Sum to Zero at the Same Point

There are various different types of receptor fields in the eye. These different types of receptor fields do not all sum to zero at the same point in physiological color space. The test subject's visual system seems to be having trouble compensating for the different "zero" points and integrating them into a unified output.

This appears to be in stark contrast to the performance of the normal population where the crossing of the + R - G and + B -Y Receptors Field null axis has traditionally been used as the physiological definition of white light., which gives maximum optical visual performance.

The Receptor Fields System That Does Not Sum To Unity

It is obvious from this experimental data that the receptor field system as a whole (whether it consists of two or 16 different types of fields) is not summing to a single unity output in this individual. The visual performance is dependent on the part of the spectrum that is energizing the eye.

This is contrary to the normally accepted Receptor Field Theory of Vision, which holds that the vision system should sum all the output signals of the receptor fields to a single visual unity in the vision-processing centers of the brain. This is obviously not happening in this individual and different receptor fields are producing different performance for different spectral energy inputs.

Again from this experimental data, it is not possible to determine a physiological cause, only that the effect exists.

An Integration Problem in Vision Processing System of Test Subject

It is obvious from these test results that the subject has some type of a sophisticated problem integrating the outputs of the various receptor fields of his vision system. All the data in the form of color perception are actually available to the test subject. He is in no way color blind in any classical sense of the term. In fact, if anything, he appears to respond well to changes in color (spectral frequency energization) inputs. It does appear, however, that the test subject does not process those data in a normal manner.

Whether this is a processing problem rather than a pure vision problem is debatable and can not be determined from the existing experimental test data. There are undoubtedly experts that will argue both points of view. The truth is that our present knowledge base is to small to rule out either hypothesis at the present time. By the same token, we cannot rule out the hypothesis that there is a processing problem, but that the processing problem may have a physical vision cause.

Our difficulty in reaching a conclusion regarding the ultimate cause of the Irlen phenomenon lies partly in the current state of the Receptor Field Theory of Human Vision itself. This theory of human vision is relatively new (about a decade old) and the physiology behind it is not well understood or agreed upon. Many aspects of it are still being considered tentative and somewhat controversial.

To make matters worse, the Receptor Field Theory Vision is not yet well integrated with many of the older basic concepts of what we know of human vision and were explained in the context of the older theories of human vision. As a result many aspects of human vision are still explained, even in relatively modern textbooks, in terms of only the older classic theories of human vision. Even though technically we know that if Receptor Field theory is correct: it can't in reality work that way. As a result, some aspects of the discussion of the eye's operation in this report may appear to be ground breaking. In reality they are not, but are simply reiterations of some of the basic concepts of human vision, restated in Receptor Field Vision Theory format. They are based on the simple

extension of the basic knowledge of human vision into the framework of the new theory of vision.

The other problem that we have in this regard is that there is in reality not one currently unified and agreed to Receptor Field Theory of Human Vision that is accepted by the scientific and medical community, but in reality there are several slightly conflicting theories about the nature of the receptor field system of vision. The conflicts in particular concern the number of types of receptor fields in the system, the quantity of each type, their internal proportional composition, and the nature of the physical structure of the receptor fields themselves.

In regard to physical structure, the two major schools of thought are (1) that receptor fields are a physical reality and exist in essentially the manner shown in the diagrams presented earlier in this report, and (2) that they are not a real physical structure, but are a set of overlapping sensory arrays composed of cellular nerve (wire) connections out of a random array matrix of cone cells. There is even a sub-corollary to this latter theory, which says, "yes, but the individual cones cells are in reality connected to more than one receptor field and thus provide multiple inputs to several overlapping receptor fields," which inputs are then integrated into a single image in the vision processing centers of the brain.

For the proposes of this study and analysis, we have adopted the prevailing majority option of the scientific and medical community that receptor fields are a physically real structure (a position that is actually based on the physiological study of Rhesus monkeys rather than humans[93]).

The problem with this from the point of view of determining the base cause of the Irlen phenomenon is that depending on which physical form of receptor field construction one holds to be correct, the point of view affects the answer about what one believes the base cause of the Irlen phenomena.

What we can say is that this experiment shows that the base causes of dyslexia—or at list for this sub-group—we somehow related to the physical structure, operation output or processing of the receptor field vision system of the eye.

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[93] Part of the problem is that the physiological structure appears to be easier to find in Rhesus monkeys than in humans. Therefore, the scientific community is extrapolating its findings in Rhesus monkeys to higher primates. This is probably basically sound in general form but questionable in specific detail.

Appendix E
SUBJECTIVE FACTOR RECEPTOR FIELD ENERGY PLOTS

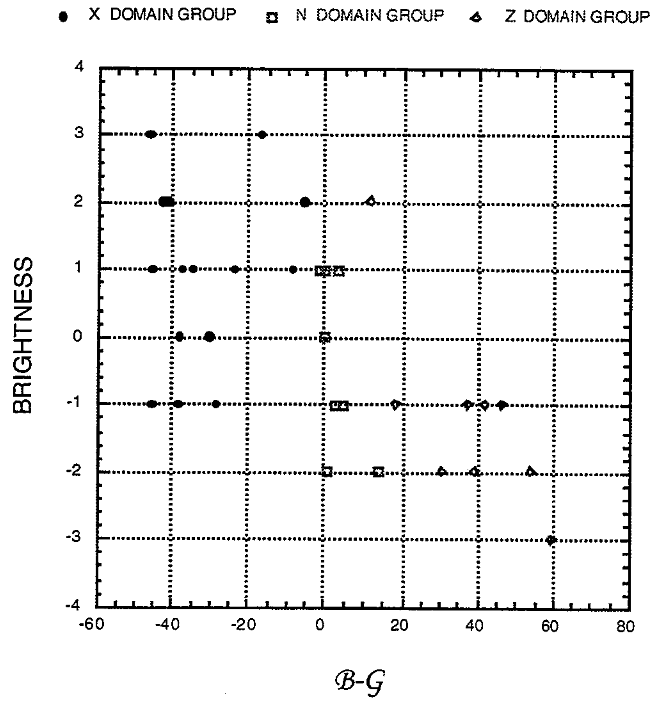

FIGURE E-1. Rationalized $\mathcal{B}$-$\mathcal{G}$ Receptor Field Energy vs. Brightness.

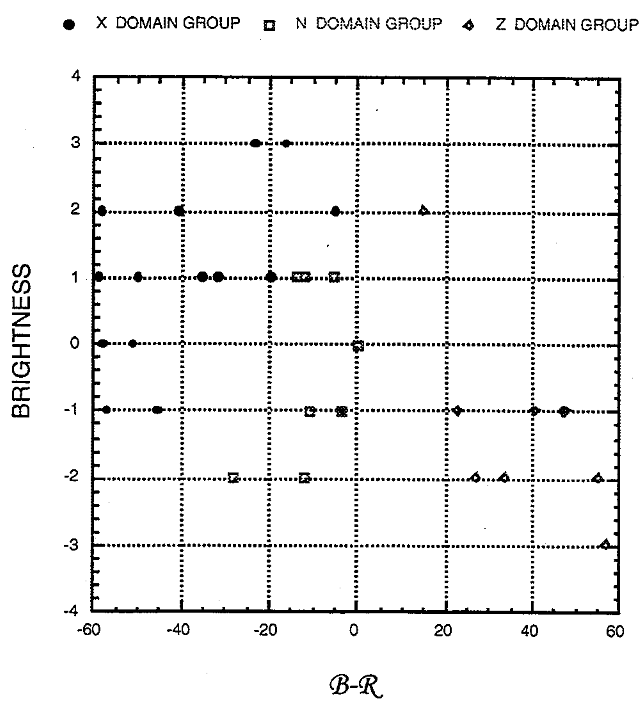

FIGURE E-2. Rationalized $\mathcal{B}$-$\mathcal{R}$ Receptor Field Energy vs. Brightness.

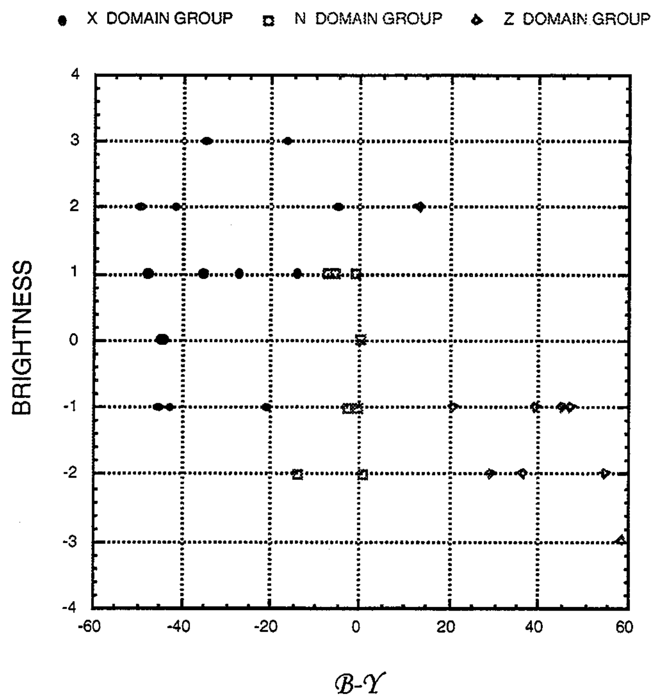

FIGURE E-3. Rationalized ℬ-𝒴 Receptor Field Energy vs. Brightness.

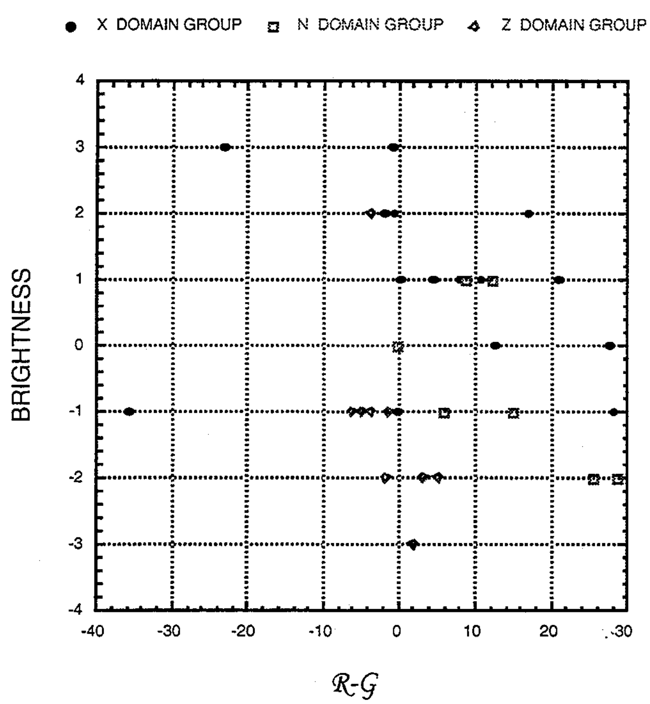

FIGURE E-4. Rationalized ℛ-𝒢 Receptor Field Energy vs. Brightness.

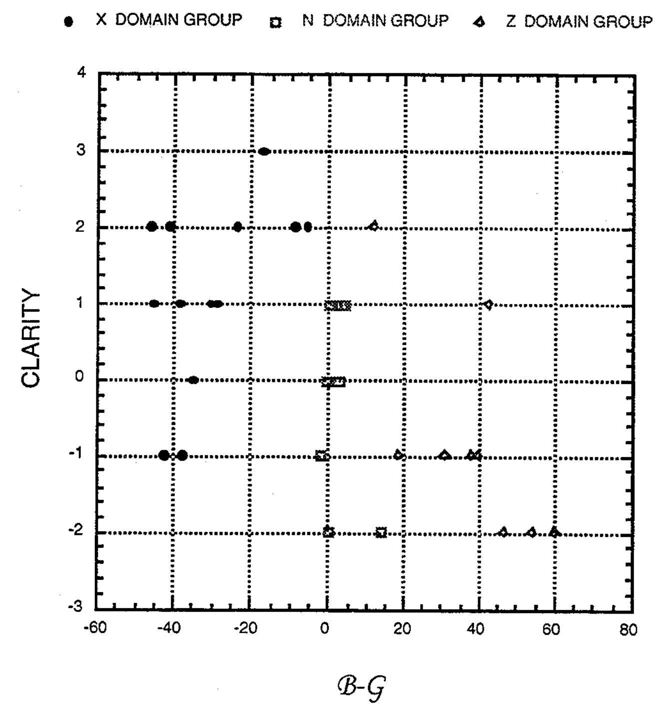

FIGURE E-5. Rationalized $\mathcal{B}$-$\mathcal{G}$ Receptor Field Energy vs. Clarity.

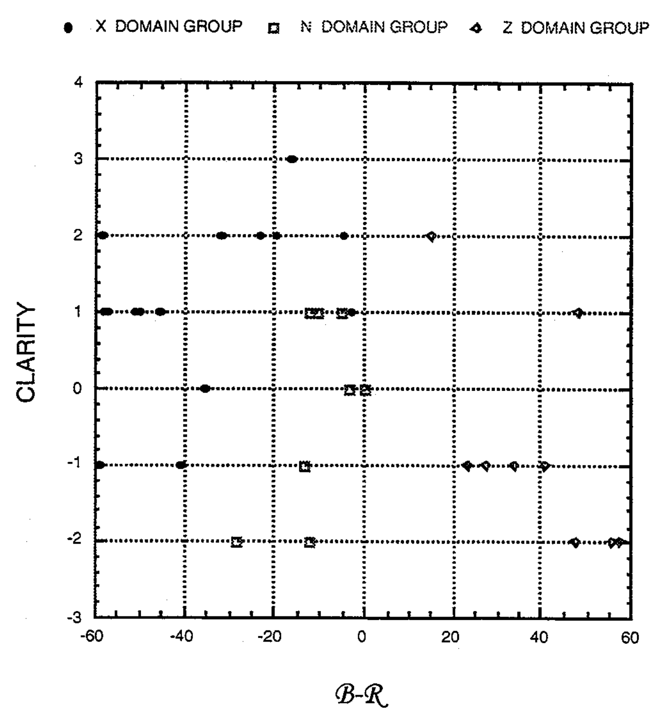

FIGURE E-6. Rationalized $\mathcal{B}$-$\mathcal{R}$ Receptor Field Energy vs. Clarity.

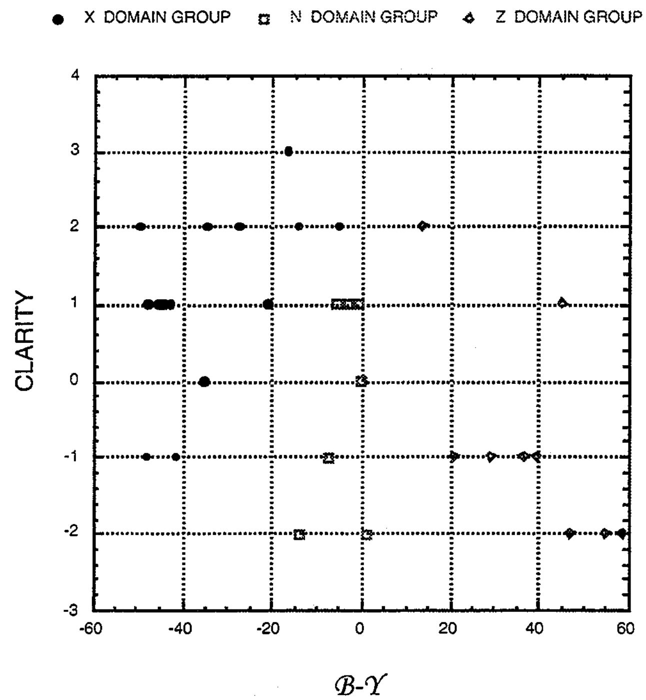

FIGURE E-7. Rationalized ℬ-𝒴 Receptor Field Energy vs. Clarity.

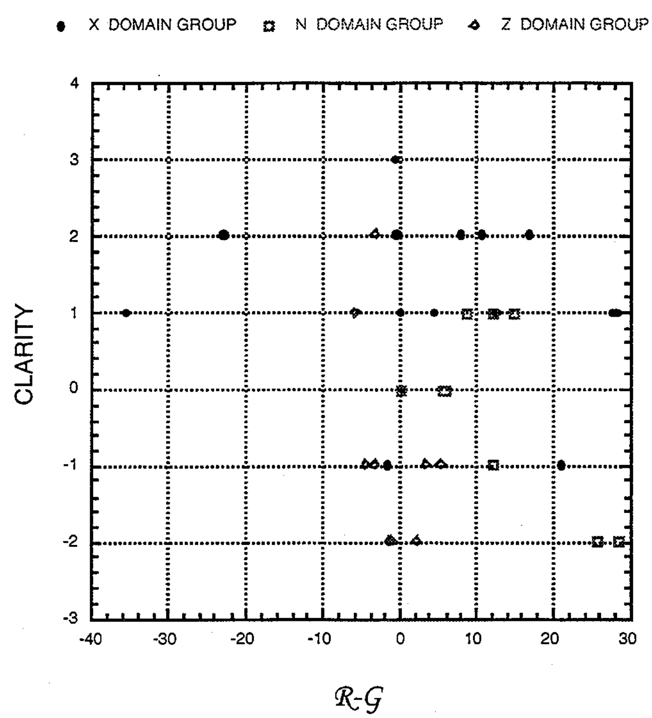

FIGURE E-8. Rationalized ℛ-𝒢 Receptor Field Energy vs. Clarity.

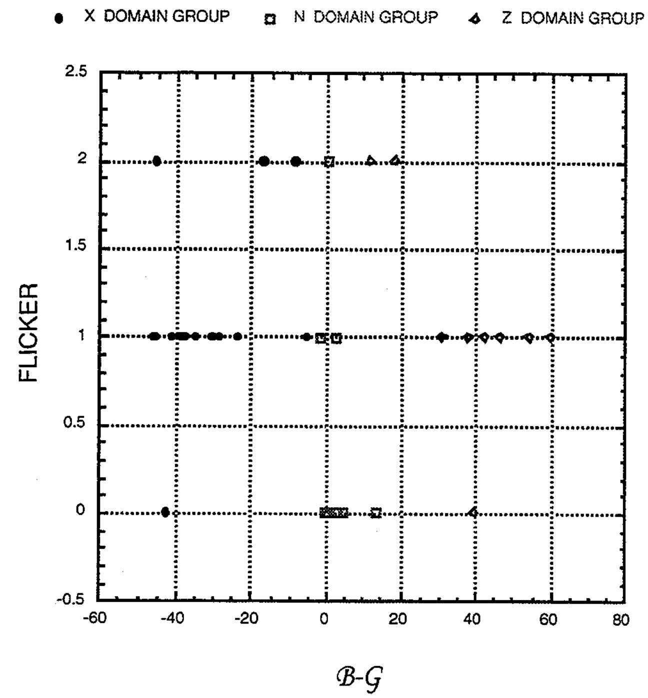

FIGURE E-9. Rationalized ℬ-𝒢 Receptor Field Energy vs. Flicker.

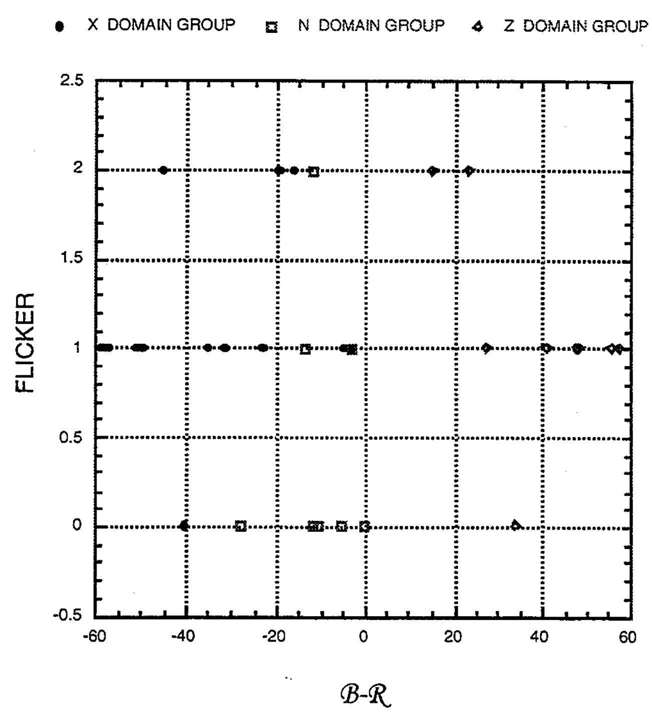

FIGURE E-10. Rationalized ℬ-ℛ Receptor Field Energy vs. Flicker.

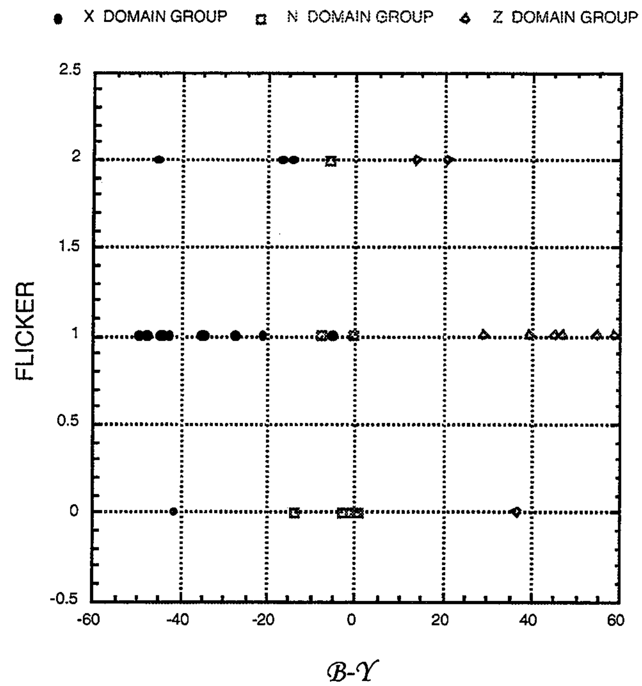

FIGURE E-11. Rationalized B-Y Receptor Field Energy vs. Flicker.

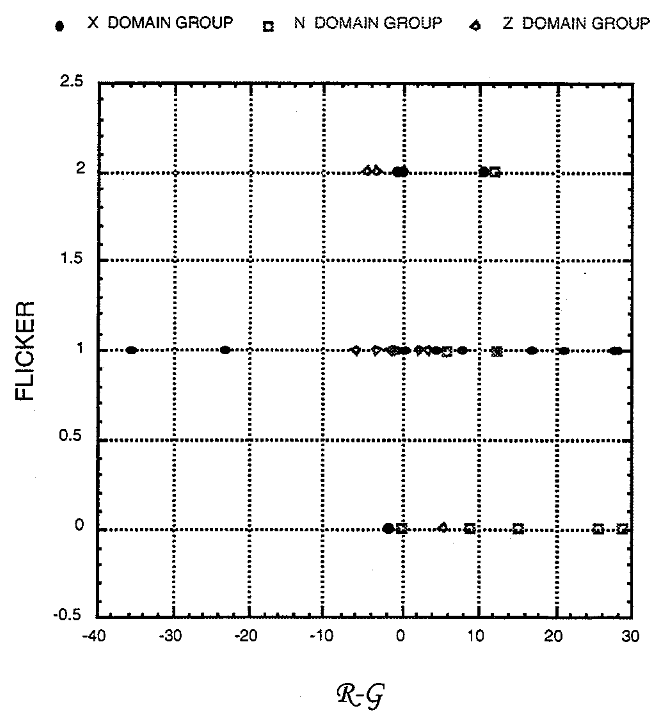

FIGURE E-12. Rationalized R-G Receptor Field Energy vs. Flicker.

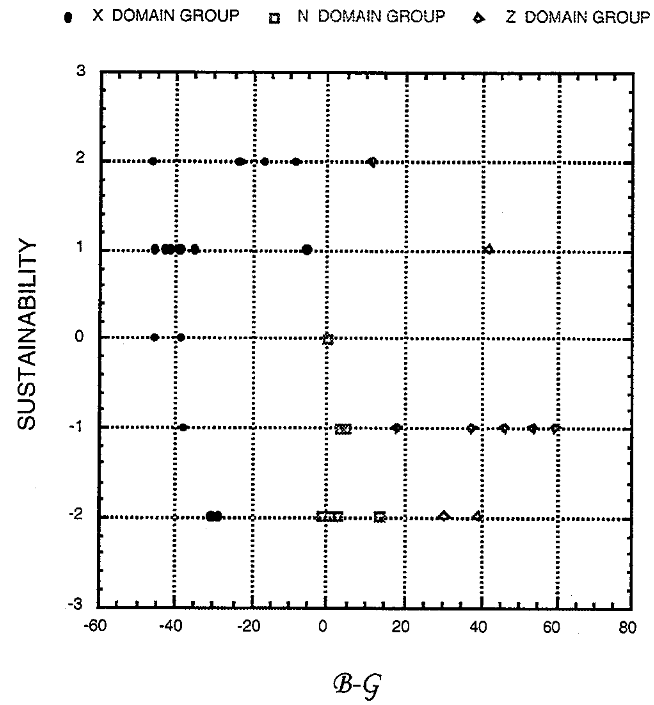

FIGURE E-13. Rationalized ℬ-𝒢 Receptor Field Energy vs. Sustainability.

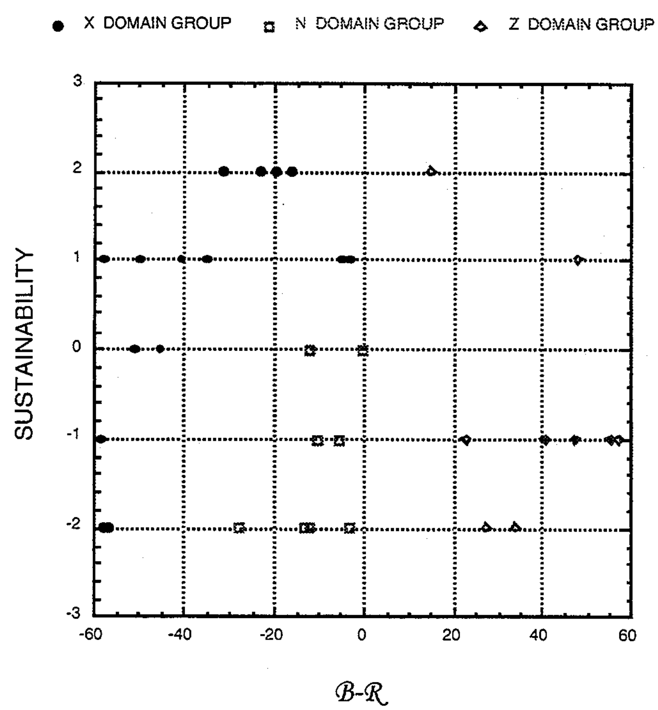

FIGURE E-14. Rationalized ℬ-ℛ Receptor Field Energy vs. Sustainability.

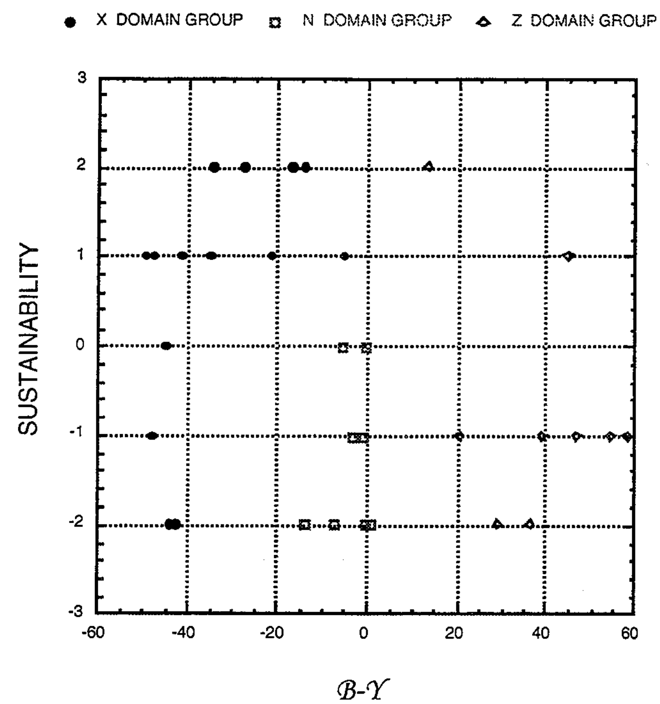

FIGURE E-15. Rationalized ℬ-𝒴 Receptor Field Energy vs. Sustainability.

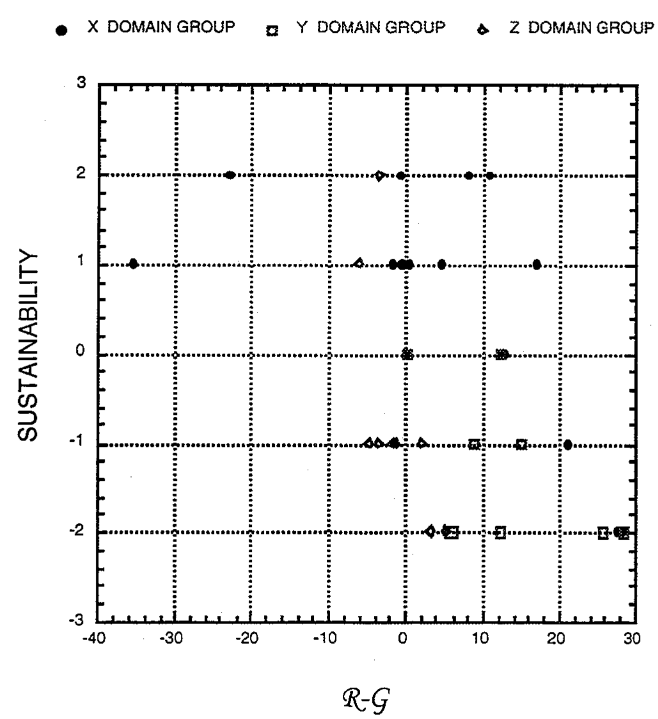

FIGURE E-16. Rationalized ℛ-𝒢 Receptor Field Energy vs. Sustainability.

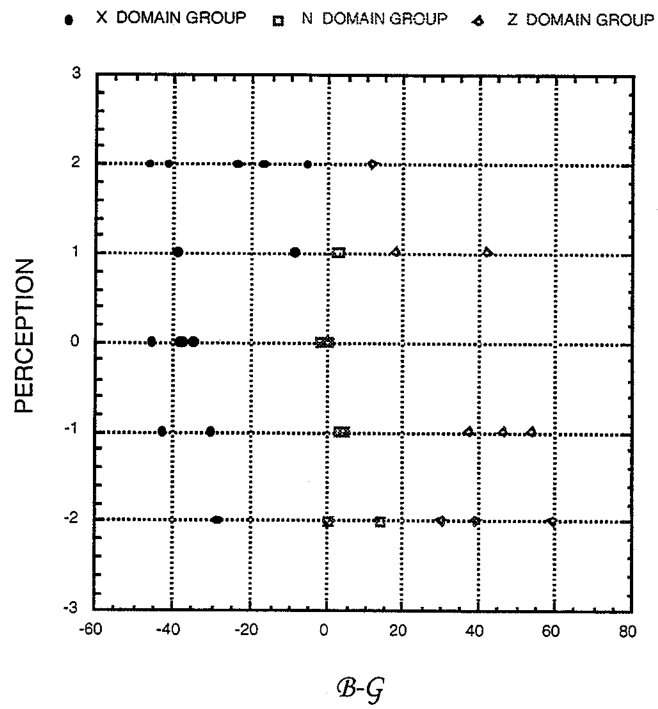

FIGURE E-17. Rationalized ℬ-𝒢 Receptor Field Energy vs. Perception.

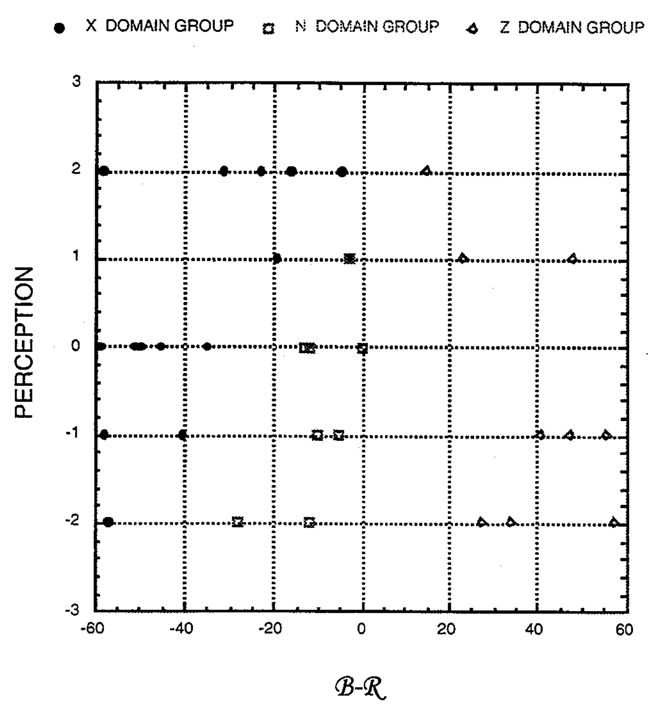

FIGURE E-18. Rationalized ℬ-ℛ Receptor Field Energy vs. Perception.

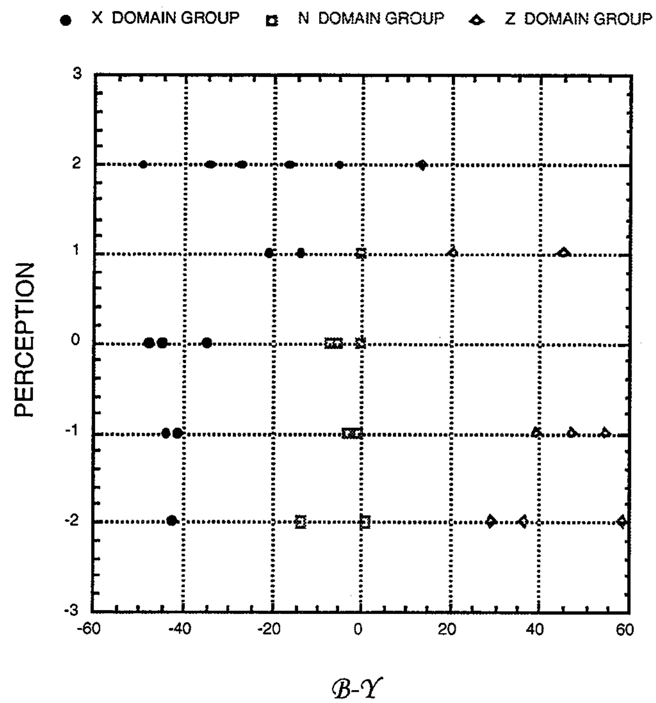

FIGURE E-19. Rationalized $\mathcal{B}$-$\mathcal{Y}$ Receptor Field Energy vs. Perception.

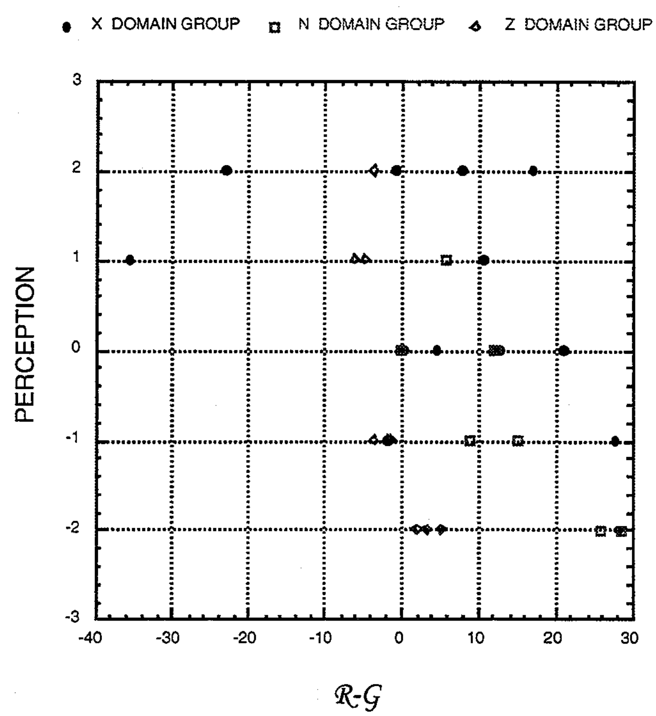

FIGURE E-20. Rationalized $\mathcal{R}$-$\mathcal{G}$ Receptor Field Energy vs. Perception.

Appendix F
MISCELLANEOUS OBSERVATIONS

This appendix records miscellaneous observations of the subject observer for future reference. No attempt to quantify them was made at the time of their recording.

1. The observer has noted that he finds it easier to read in dimmer light.

2. The observer finds that the angle of light in relation to his eye has an important effect on his reading ability. The subject reads significantly better if the light comes from behind him with no bright spot visible in his field of vision. A forward angle of in-coming light seems to have deleterious effects on both vision span and reading ability. The worst of all possible cases appears to occur when the light source is to the side of and at right angles to the center line of the eye. Though an obtuse angle with a bright spot in the back peripheral vision zone is also terrible.

3. The observer has noted that there is a substantial tube effect in that conscious eye span is much better if the observer is looking down a long unlighted hall, tunnel, or tube at a lighted object. This presents all the light reaching him actually parallel to the axis of the eye.

4. The observer noted the following phenomenon involving flicker. The subject was in a room where a large ceiling fan was between him and the light source. This produced a very visible flicker on the page. The subject was almost unable to read in this environment.

5. The observer has noted that his eye span and reading ability are seriously affected by the type of fluorescent bulb he is under, a cool white bulb being much worse to read under than a light white bulb.

6. The test subject reported that after reading for a while under some color conditions where he was having difficulty reading, it took some time for this effect to go away and for him to be able to read normally under normal white-light conditions. (This means that there should be some break better experiments with different color filters.)

7. The observer noted that he sees much better under low-pressure sodium street lights.

8. The observer feels that his vision span goes down when looking at letters on a black and white producing color CRT screen.